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HYDROMETEOROLOGICAL REPORT NO. 57

(SUPERCEDES HYDROMETEOROLOGICAL REPORT NO. 43)

PROBABLE MAXIMUM PRECIPITATION - PACIFIC NORTHWEST STATES

Columbia River (including portions of Canada), Snake River and Pacific Coastal Drainages

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ABSTRACT This study provides all-season general-storm probable maximum precipitation (PMP) estimates for durations from 1 to 72 hours for the Columbia River basin, the Snake River basin and drainages along the Pacific coast. This includes the states of Washington, Oregon, Idaho, western Montana, northwestern Wyoming and parts of Canada. PMP estimates and their seasonal variation are given for area sizes ranging from 10 to 10,000 square miles.

Estimates are also provided for local-storm PMP in the region, covering durations from 15 minutes to 6 hours for drainage areas from 1 to 500 square miles. In a significant departure from its predecessor, this study extends local-storm PMP estimates to areas west of the Cascade Mountain divide. Another significant change is the lowering of 6/1-hour ratios for local storms, reducing PMP at longer durations.

Step-by-step procedures are given for computing PMP for both the general- and local-storm criteria. Example computations are furnished. Numerous comparisons are presented between the results of this study, its predecessor and other extreme storm criteria such as the 100-year rainfall frequencies found in NOAA Atlas 2. These results indicate that this report provides consistent and reasonable estimates of PMP.

Several new techniques and procedures were developed in order to attain the goals of the study. Chief among these was the development of a computerized storm analysis procedure, which was used to study 28 major storms affecting the region. New 3- and 12-hour maximum persisting dewpoint climatologies were also produced in order to better assess the moisture available for precipitation.

has contained maximum efficiency. This assumption is necessary because not all aspects of the physical processes resulting in the most extreme rainfall are known. PMP estimates are the result of envelopment and smoothing of a number of moisture maximized, transposed storm rainfall amounts. This report will discuss these procedures as applied to Pacific Northwest storms.

The concept of PMP as an upper limit often evokes concerns that the procedure combines maximized quantities to reach a level that cannot reasonably be expected to occur. It will be noted in this study, as in past NWS studies, that this is not the case. While moisture is indeed maximized, numerous other factors are involved at a lesser level to effectively control unreasonable compounding of extremes.

Terrain plays an important role in precipitation and can act both to enhance as well as reduce (shelter) observed rainfall. It is well known that storms that move slowly or become stalled, or reoccur over a specific location result in more precipitation falling in a particular rain gage than do rapidly moving storms. Thus, orographic effects from storm-terrain interactions to the extent that they trigger moisture release or block storm movement, play an important role in PMP studies. The Pacific Northwest has some of the most complex terrain features in the country and makes this region a difficult, although interesting, challenge for study.

1.3 Authorization

The authorization to determine an updated PMP report for the Northwest states was given by the U.S. Army Corps of Engineers Office of Civil Works in cooperation with the Bureau of Reclamation Flood Section. Appropriations supporting the NWS effort were provided through a continuing Memorandum of Understanding between NWS and COE and a redesignation of the Interagency Agreement signed by NWS and Reclamation.

The Department of Agriculture Soil Conservation Service (SCS) has continued its long participation in the joint agency group that meets every four to six months to oversee progress on NWS hydrometeorological studies. These review meetings, comprised of field and headquarter representatives from SCS, COE, Reclamation and NWS, were begun in the late 1970's to improve interagency communication on hydrometeorological studies of mutual interest and to provide a forum to discuss progress on ongoing studies. The regular attendees to these meetings are referred to as the Joint Study Team. Recently, the Federal Energy Regulatory Commission (FERC) joined this team.

1.4 Study Region

The region of study in this report is the same as that shown for HMR 43 except for an expansion of the portion of the Columbia River drainage in southern British Columbia. Through joint agency agreement, and after discussions with officials from B.C. Hydro (Canada), it was judged that the Canadian Columbia River drainage, important to the study region, be limited to that portion of the drainage below Keenleyside Dam (formerly known as Arrow Dam) in British Columbia. Figure 1.1 shows the total region.

1.5 Scope of Study

This study recognizes two categories of storms for the region considered; general and local storms. General storms are major synoptic events that produce precipitation over areas in excess of 500 mi^2 and over durations often much longer than 6 hours. Local storms have durations up to 6 hours and cover areas up to 500 mi^2. Particularly in the western United States such local storms often occur independently from any strong synoptic weather feature. Climatological observations show that both these storm categories can occur at any time throughout the Pacific Northwest. However, general storms are least dominant during summer months and most intense west of the Cascade Mountain ridgeline. Local storms are by comparison usually a warm season feature and are most often observed east of the Cascades.

.The Joint Study Team mutually agreed that the study of general-storm PMP be limited to areas of 10,000 mi^2 and durations of 72 hours, or less. Local-storm PMP estimates in this study are limited to areas of 500 mi^2 or less and durations up to 6 hours. Both general- and local-storm PMP estimates are provided for the entire region. Seasonal variations are also included. A lesser number of storms were used to evaluate the temporal distribution of incremental amounts for both general and local storms.

1.6 Method of Study

The study of general-storm PMP in this report continues the evolution of the storm separation method applied in the development of PMP for the Rocky Mountain eastern slopes (Hansen et al., 1988). The storm separation method is particularly applicable to orographic regions where the more traditional method of explicit storm transposition is inappropriate.

The storm separation method is used to examine extreme storms of record that have occurred in and near the study region. Such storms are "separated" into convergence (non-orographically influenced) and orographic (terrain influenced) components of precipitation. The convergence component of storms is treated as though no significant topographic features were present in and upwind of this storm area, and then moisture maximized and transposed within zones considered meteorologically homogeneous. The orographic component of the storms, however, is not directly used in computing total PMP. Instead, an orographic enhancement procedure is developed from relationships between an orographic factor derived from NOAA Atlas 2 (Miller et al., 1973) 100-year analyses and a storm intensity factor. These are described in considerable detail in HMR 55A (Hansen, et al., 1988), and summarized for this study in Chapter 8.

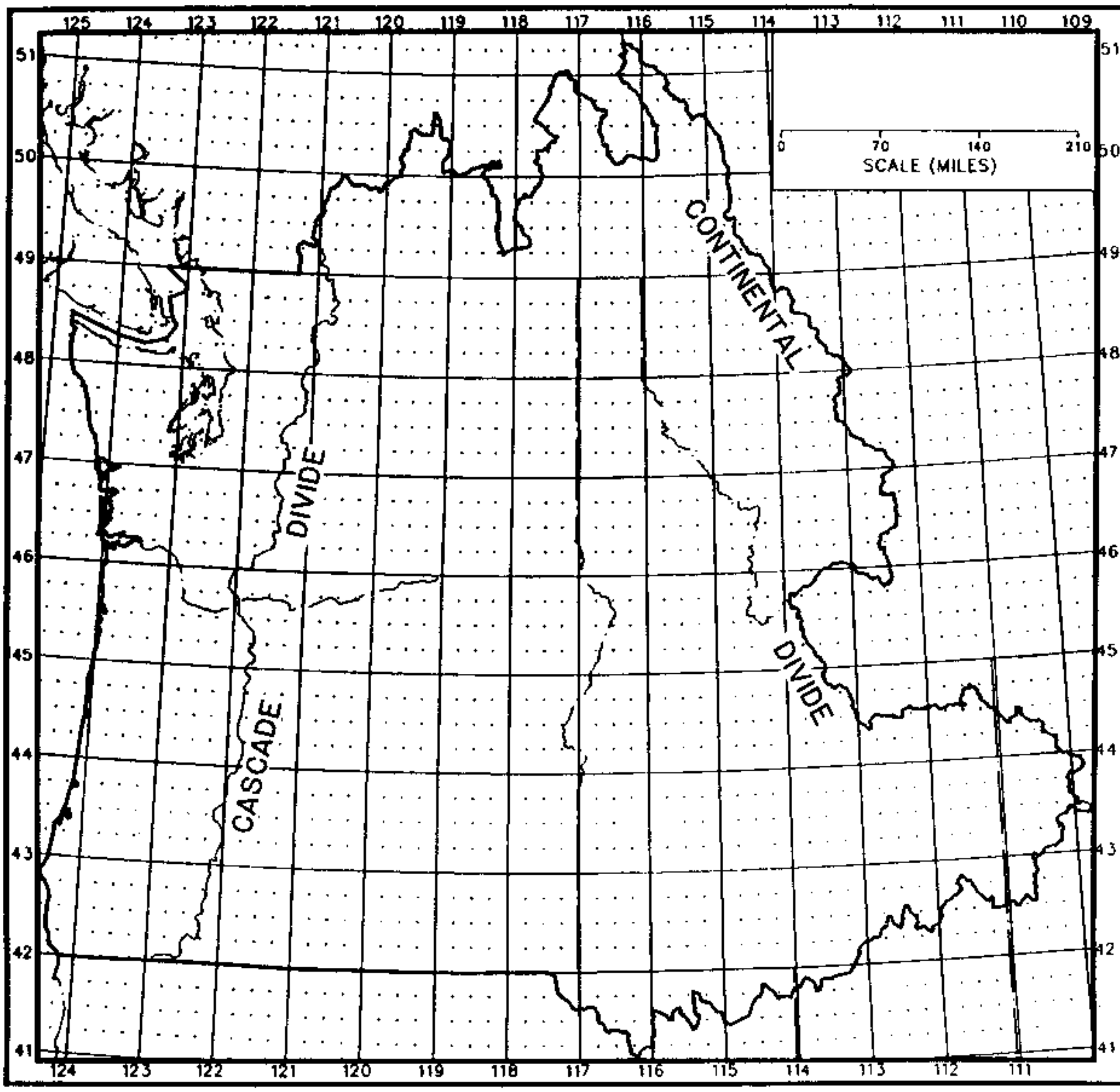

Figure 1.1.--Base map showing the Pacific Northwest region covered by this study.

The method allows for computation of general-storm PMP for an index area/duration (10 mi^2 and 24 hours in this study), and provides relations that enable other durations and areas to be obtained.

Local storm PMP has been developed much in the manner of past studies (Hansen, et al., 1977; Hansen, et al., 1988), where data records are searched for maximum 1-hour events, that are combined with known extreme events of 6 hours or less to form a data base. All major observed storm events are normalized to 1-hour moisture maximized values and adjusted to 1000 mb. In this study, a particular effort was made to provide local storm PMP estimates west of the Cascade Divide, where they were not provided in HMR 43 (USWB, 1966).

1.7 History and Rationale

The need to revise and update HMR 43 has developed over the intervening years as the result of a number of developments. At a meeting in San Francisco in October 1982, various Federal agency representatives discussed a wide variety of hydrometeorological topics up for consideration. There was joint agreement that revision of HMR 43 be given highest priority. Some of the reasons leading to this conclusion are given in Table 1.1.

In Table 1.1, the problem listed first was recognized by Schaefer (1980), when detailed grid comparisons were made between NOAA Atlas 2 (Miller et al., 1973) 100-year values and general-storm PMP for short durations (<6 hours) from HMR 43. NOAA Atlas 2 was completed after HMR 43. Typically, 100-year precipitation values from NOAA Atlas 2, are analyzed in checking consistency and magnitude of PMP estimates. The ratio of PMP to 100-year amount at any location is expected to be greater than one. In past studies, the ratios range between two and seven, depending on distance from moisture source(s) and type of terrain.

Another problem in Table 1.1 developed from concern about use of the laminar flow model for determining orographic precipitation in HMR 43. The model was first applied to and calibrated against the western slopes of the Sierra Nevada Mountains in California to aid in determining general-storm PMP for California in HMR 36 (USWB, 1961). Transfer of this technique to the northwest states in HMR 43 necessitated some additional adjustments that brought about concerns for the resulting adequacy of this method.

The remaining items in Table 1.1 are self explanatory. Over the period of time since HMR 43 was published, the NWS Hydrometeorological Branch has developed a new procedure for development of PMP in orographic regions. This approach has evolved through a series of studies (Miller et al., 1984; Fenn, 1985; and Hansen et al., 1988). It is this procedure that is applied to storm data in this study.

Table 1.1.--Compilation of reasons considered as basis for joint agency decision to revise HMR 43 (USWB, 1966).	
1.	Instances were found where ratios of short-duration general-storm PMP to precipitation frequency values were near or below unity, particularly west of the Cascades.
2.	Questions regarding the technical adequacy of procedures used in developing HMR 43 were raised, in particular the application of the laminar flow model for orographic precipitation.
3.	Recent capability to process extreme storm data through automated techniques to obtain DAD information.
4.	Recent capability to apply new technical procedures developed over time for determining PMP in orographic regions (the storm separation method).
5.	A need to determine PMP estimates for larger basin areas throughout the region required depth-area relations to larger areas.
6.	A need to determine local storm PMP estimates west of the Cascade Divide.
7.	A need to consider storms that have occurred since the 1950's.
8.	A need to provide a better tie-in to neighboring PMP studies.
9.	A need to expand the region of coverage in southern British Columbia.

An alternative source of information about this procedure is available in somewhat less detail in the World Meteorological Organization (WMO) Operational Hydrology Report No. 1 (1986).

In mid-1985, the present study was interrupted for over two years to allow modifications to be made in the HMR 55A study. In early 1988, work on the revised Pacific Northwest PMP study resumed and culminates in the present report, referred to as HMR 57.

1.8 Reclamation Cooperation

This study is primarily the product of the NWS Hydrometeorological Branch, and represents the latest understanding and technology resulting from more than 50 years experience in developing PMP estimates. NWS wishes to acknowledge, however, that major efforts of the Reclamation Flood Section in Denver were instrumental in those areas requiring automated processing of data and maps. Some of these efforts will be noted further in the section dealing with the automated precipitation data analysis (APDA) procedure, but it should be mentioned here that Reclamation had a major role in the completion of this study. Reclamation was responsible for providing the material contained in Chapters 5 (APDA) and 12 (Test Basin Analysis).

The cooperation between these two hydrometeorological staffs has brought an added strength to the product as well as bonding between researchers. Reclamation has played a major role in reviews and decisions concerning storm selection, storm processing, digitizing analyses, testing results, and almost every aspect of this effort. Although Reclamation is at the same time one of the primary users of these results, it is believed that this dual role has enhanced the integrity of this effort.

1.9 Peer Review

A major criticism of HMR studies in the past has been the limited internal review process. In most instances, the reviews were limited to those agencies represented on the Joint Study Team. Initially, the limitation was believed justified under the reasoning that only these agencies had sufficient knowledge and understanding to provide adequate review.

Interest in PMP and the economic consequences of structure modifications required to design for PMP required by the National Dam Inspection Act of 1972 have brought new interest in the concepts and procedures being applied. Over the last 10 to 15 years, PMP and its usage has become the subject of numerous studies and conferences (NRC, 1985; OWDC, 1986; NRC, 1988; ANCOLD, 1988; and FEMA, 1990). As a result, many more people have become familiar with the concepts and applications involved in PMP studies. Equally true is the fact that many have questioned these studies and their reliability. Some of these concerns have lead to independent studies (EPRI, 1993a; 1993b), while still others have turned away from the PMP approach preferring to seek probabilistic methods.

In view of the concerns expressed by many that the NWS studies should be subjected to more widespread review, we have offered this report to the following outside agencies:

1. Dam Safety Section
   Department of Ecology (Dr. Mel Schaefer)
   Water Resources Program
   State of Washington

2. Hydroelectric Engineering Division
   Hydrotechnical Department
   BC Hydro and Power Authority (Pat Neudorf)
   Canada

3. Hydroelectric Generation and Renewable Fuels
   Electric Power Research Institute
   Palo Alto, California (Dr. Douglas Morris)

4. Mr. Catalino Cecilio
   Consulting Hydrologic Engineer
   931 Park Pacificia Avenue
   Pacifica, CA 94044-4414

5. Department of Water Resources
   Division of Flood Management (Maurice Roos)
   1416 Ninth Street - P. O. Box 942836
   Sacramento, CA 94236-0001

6. North American Weather Consultants
   1293 West 2200 South (Dr. Ed Tomlinson)
   Salt Lake City, UT 84119

7. Canadian Climate Centre
   Atmospheric Environment Service (William D. Hogg)
   4905 Dufferin Street
   Downsview, Ontario M3H 5T4
   Canada

We extend our sincere appreciation for the competent and constructive reviews given by all reviewers. It is hoped that this report has been strengthened by the interaction with such a cross section of the hydroelectric and hydrometeorologic community.

1.10 Organization of the Report

This report follows a style used in similar studies produced by the NWS over the last 20 years. The text describes, in general, background information relating to the data, the analyses and the methods used in developing PMP index maps. In this report Chapters 2-11 provide this discussion. Chapter 12 provides results from application of the PMP estimates to 47 individual basins for the purpose of judging the overall acceptability of the results. Chapter 13 gives study results compared to other precipitation and PMP indices. Conclusions and recommendations are covered in Chapter 14.

Chapter 15 is probably the most important chapter in the report, as far as most users are concerned. This chapter provides the information, both the stepwise procedure and the tables and figures, required to make a PMP estimate for a specific site. To reduce the need for shuffling through pages in the report, all tables and figures used in the procedure have been repeated in this chapter to make it self-contained. Figures and tables are cross-indexed to the text that explains their origin should the user find the need for more information. Also, since the general storm index maps are oversized (at 1:1,000,000 scale), they are provided separately from the main report.

Finally, the references called for in the text are given, followed by five rather extensive appendices that cover (1) storms of record considered in this study, (2) selected storm synoptic and depth-area-duration (DAD) data, (3) the storm separation method (SSM), (4) local storm details, and (5) snowmelt criteria.

The numerous references to certain past studies, such as Hydrometeorological Report 43 and NOAA Atlas 2 make it impractical to always include the technical reference. Therefore, after the initial complete reference is given, these commonly referenced works will simply be noted as HMR 43, HMR 55A, NOAA Atlas 2, etc. Less commonly referenced material will be noted by the customary author/date references.

2. SIGNIFICANT STORMS

2.1 Introduction

One of the prime reasons for undertaking the revision of the 1966 Pacific Northwest PMP study was to give greater consideration to storm data. That is, PMP development throughout the non-orographic eastern United States is based on a sample of extreme storms, while in the West so-called alternative approaches have been employed in lieu of adequate storm data. HMR 43 relied on a very limited number of storms to establish an index precipitation-to-moisture ratio (P/M) value at Portland, Oregon. A gradient of P/M ratios was established from three storms using data points in central California. No storm data were available east of the Cascades. The general pattern to provide P/M ratios throughout the region was based on a January dew point analysis. Only two storms (11/18/50, 12/21-23/55) were used to develop the parameter values used in the orographic model, which was then tested against an additional seven storms. Other storms were considered to aid in developing depth-duration and seasonal relations. HMR 43 does not include depth-area-duration (DAD) data for any storms.

For the present study, a review was made of storms that occurred throughout the Pacific Northwest from roughly 1900 to 1980. Various data sources were examined to complete a master listing of storms. Initially, the Corps of Engineers Storm Rainfall Catalog (USCOE, 1945-) provided a foundation of information from which some depth-area data were available. Most storms in this record between 1901 and 1945 (Appendix 1) came from this Storm Catalog, while Reclamation and NWS files were used to supplement the list.

These storms were primarily general storms, that is they had durations exceeding 12 hours and precipitation was widespread as a result of a major synoptic-scale disturbance (low pressure system or strong frontal activity). A few storms in the master list turned out to be local storm events, usually intense convective storms of short duration. The geographical distribution of the storms listed in the master file is shown in Figure 2.1. The list includes a few storms whose maxima occur within a couple of degrees south of the region of interest. The primary centers (see Appendix 2) for storms 156 and 165 occur in California outside the region shown on Figure 2.1.

Because of the distribution of observing stations, the maxima for a number of storms occur at common locations. In particular, numerous events are centered at Forks, Quinault, and Snoqualmie Pass, in Washington; Glenora, Valsetz, and Illahe, in Oregon; Deadwood and Roland in Idaho. It is possible that certain terrain features at each of these locations serve to enhance precipitation in passing storms. More on this will be discussed in Chapter 3 regarding orographic effects. At the same time, there are large data-sparse areas, most notably

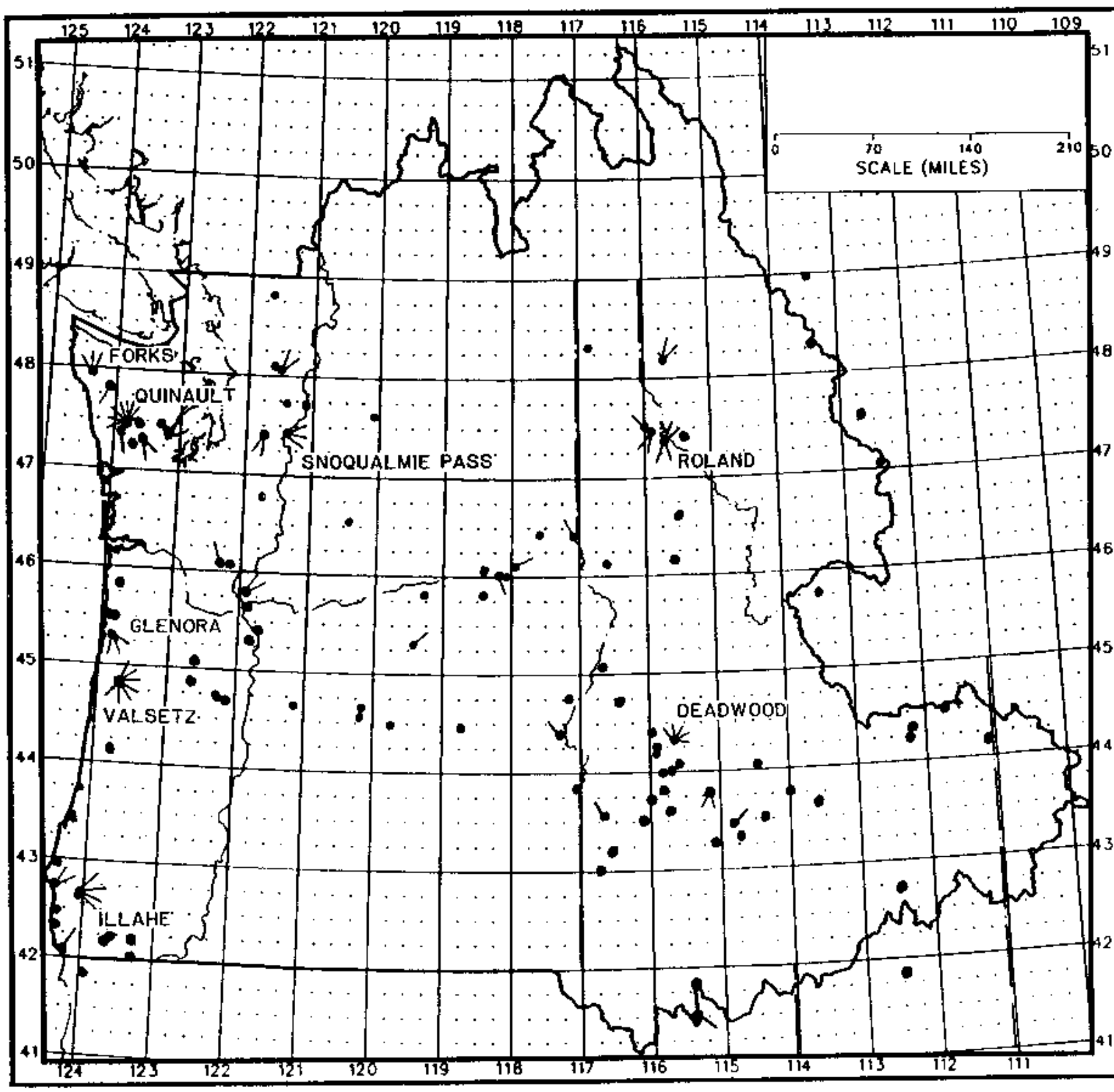

Figure 2.1.--Distribution of storm centers in master file (see Appendix 1). Multiple storms indicated by tails attached to dots.

southern Oregon (away from the coast), eastern Washington, western Montana and British Columbia. One would expect that storm tracks reaching the Pacific Coast should present a rather uniform distribution, with some increase in frequency toward the northern coast. There is, however, a significant sheltering effect by coastal mountain ranges on precipitation in the basins east of the Cascades. This may help to explain the comparative lack of data over some of the interior northwest. In Idaho and western Montana the storm concentration in the western Snake River basin appears to reflect the density of population more than any meteorological phenomena. Undoubtedly, significant rains occur within the Bitterroot Mountains to the north that go undetected.

In addition to the storms in Appendix 1, another survey was made for storms between 37 and 42°N latitudes that were considered candidate storms for transposition into the region. Primarily collected from various sources by Reclamation, Appendix 1, Table A2, lists 130 additional storms that were numbered 501 and above to distinguish them as being outside and to the south of the region. Storms 126, 156 and 165 were storms included in the initial list of major storms within the region. After study using the ministorm analysis (Chapter 5), it was discovered that the storm maximums actually occurred in California. A decision was made not to change the index numbers.

From the storms in Figure 2.1, a second selection was made to reduce the sample to those events that were the most controlling for their region. In order to make this selection, various subregions were delineated such as coastal, western Cascades, eastern Cascades, interior Washington/Oregon, Idaho and western Montana, and Continental Divide slopes. A final selection was made from the master list (Appendix 1, Table A1) to distribute the storms as much as possible through these subregions and with consideration for the magnitude of precipitation. Despite these attempts, there was some geographical clustering while large areas still have no major storms. Twenty-eight storms were finally selected for ministorm analysis and these form the foundation for the revised analysis.

The 28 priority storms (United States) are listed in Table 2.1 and their geographical distribution shown on Figure 2.2. When comparing locations (lat./long.) of maxima between Table 2.1 and the locations given in the master list (Appendix 1), one finds minor differences. The reason for these differences are that the storm analysis procedure showed that the storm maximums had different centers than previously believed (see Chapter 5).

It should also be noted that Table 2.1 includes two storms in or near British Columbia, Canada, Seymour Falls (SEY) and Mount Glacier (MTG). Since this study includes a portion of lower British Columbia, as discussed earlier (Figure 1.1), it was necessary to locate storms that may be important to thissubregion. Available Canadian storm data sheets were surveyed and the Atmospheric Environment Service of Canada was contacted for updated information on major storms. A number of published reports on PMP were also

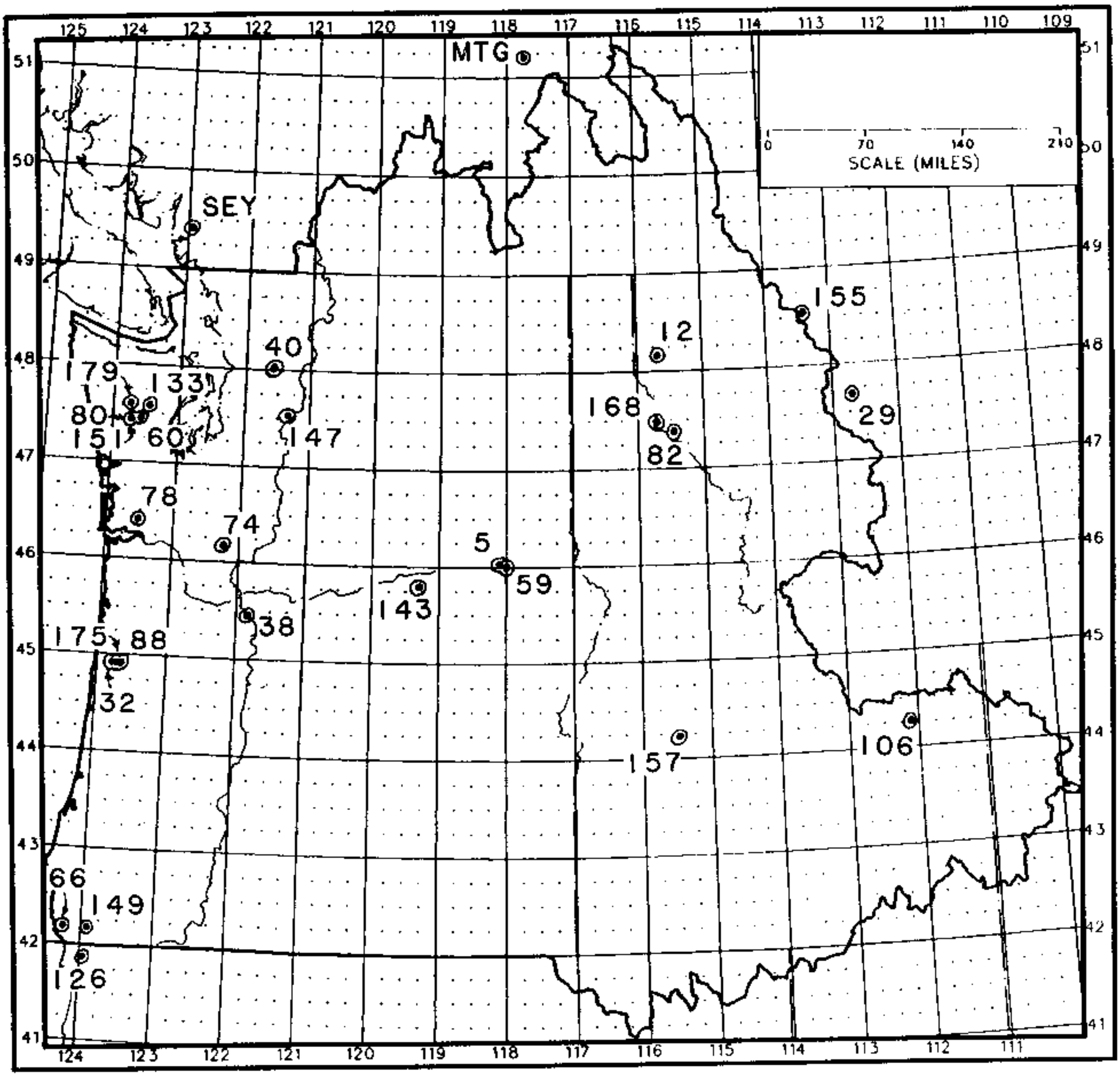

Figure 2.2.--Distribution of the extreme storms considered in this study (see Table 2.1 for identification).

Table 2.1.--Final storm sample for Pacific Northwest general storms.

Storm Number	Date	Latitude* (Deg. Min.)	Longitude* (Deg. Min.)	Barrier Elev. (ft.)	24 hr/10 mi² avg. amt.	DAD Limits Area/Duration
5	5/28-30/06	46 01	118 04	3200	6.16	16378/48
12	11/17-19/09	48 12	115 41	5800	3.87	17344/48
29	6/19-22/16	47 41	112 43	6500	7.34#	18924/72
32	12/16-19/17	44 55	123 46	1200	10.66	33167/72
38	11/19-22/21	45 28	121 52	2800	8.30	73110/72
40	12/9-12/21	48 01	121 32	3200	8.58	27253/72
59	3/30-4/1/31	46 00	118 00	3600	4.79	32730/60
60	12/17-19/31	47 28	123 35	4500	8.06	40221/48
66	3/16-19/32	42 10	124 15	1200	9.63	42243/72
74	12/19-22/33	46 10	122 13	2600	7.98	11783/72
78	10/22-25/34	46 25	123 31	1000	6.28	20559/72
80	1/20-26/35	47 28	123 43	1800	14.45	43865/144
82	3/24-25/35	47 22	115 26	5400	4.06#	23729/24
88	12/26-30/37	44 55	123 38	1500	10.76	13869/96
106	6/26-27/44	44 16	112 04	6400	4.25	41385/24
126	10/26-29/50	41 52	123 58	2000	15.84	80511/72
133	11/2-4/55	47 34	123 28	3500	12.16	41818/48
143	10/1-2/57	45 49	119 17	2900	3.40	22002/24
147	12/14-16/59	47 33	121 20	3800	8.48	29329/48
149	11/21-24/61	42 10	123 56	2700	10.90	36321/48
151	11/18-20/62	47 28	123 43	1800	12.45	4665/48
155	6/6-8/64	48 34	113 23	7300	14.35	87054/48
156	12/21-24/64	39 55	123 35	2500	16.23	99988/72
157	12/20-24/64	44 14	115 29	7100	4.89	59661/96
165	1/14-17/74	40 20	124 06	1900	10.63	81179/72
168	1/13-16/74	47 29	115 44	5200	4.42	42267/72
175	12/24-26/80	44 55	123 44	1400	9.22	24865/48
179	11/30-12/2/75	47 37	123 44	3300	9.35	31912/72
SEY	1/14-15/61	49 26	122 58	2000	14.30	150,000/126
MTG	7/11-13/83	51 13	117 44	7300	6.75	35,000/72

*Based on Entire Storm (primary centers, see Appendix 2) (# for approximate area of 15 mi²) reviewed that might provide additional storm information. From these varied sources, only two storms were selected as candidates to add to the master list for study based on proximity to the region. Upon further review of DAD data available for these storms (Appendix 2), it was decided that they would be considered only for transposition and not included in the DAD analysis. Although the Seymour Falls and Mount Glacier storms occurred near the study region, both the storms were considered to be a storm type that could also be found within the northern portions of the study region. Further detail on the use of the two Canadian storms will be given in the discussion on maximization and transposition (Chapter 7).

Therefore, the total general storm sample used in this study amounts to 30 storms. Although it is possible that some storms may have been missed by this process, it is unlikely that any omitted storm would affect the results.

2.2 Storm Data Analysis

The analysis of major storms for the Northwest states is an important part of deriving PMP estimates. The process of analysis involves collecting rainfall data from available sources; applying quality control that verifies outliers and deals with missing data; and compiling the data into a format for automated processing. Along with this step, a parallel effort is made to prepare a synoptic weather analysis. This analysis is important in understanding the timing of rainfall and in defining the storm's precipitation pattern. Synoptic discussions have been completed for some of the 30 storms listed in Table 2.1. These discussions cover the surface and upper-air features, the precipitation (including snow), and the dew point and/or temperatures pertinent to the storm. Excerpts from the complete synoptic analyses made for these storms are provided in Appendix 2 of this report.

The objective of the APDA or ministorm analysis is to obtain DAD information upon which to base the PMP index maps, as well as depth-area and depth-duration relations. Many of the older storms had long ago been designated as significant and were assigned storm index numbers by COE (USCOE, 1945-). These index numbers have two-lettered designators that identify the Corps region (division). Thus, the North Pacific Region storms are listed as NPxx-xx. The latter part of the assigned number refers to the Corps' catalog system and does not follow a chronological order. The fact that a storm has been assigned a catalog number does not signify that DAD data are available, only that the storm was recognized as a major event. Relatively few storms in the western states were processed to the degree that DAD data are available. Even fewer storms from this region were formalized to the point of published pertinent data sheets being included in the Storm Rainfall Catalog (USCOE, 1945-). Due to the lack of DAD data for Northwestern storms, a procedure to develop such data for the storms identified in Table 2.1 was established by consensus between the NWS, SCS, Reclamation and COE representatives. The automated procedure developed for this purpose is described briefly in Chapter 5.

3. TERRAIN

The terrain of the Northwest region is complex and largely responsible for the broad variations in the observed climate. Numerous mountain ridges, including the Cascade Range and the Rockies, lie perpendicular to the dominant moisture inflow directions resulting in enhanced precipitation on upwind slopes and significant reductions in precipitation to the leeward. Some of these characteristics are shown in the map of mean annual precipitation (NCDC, 1992) shown in Figure 3.1. Totals exceeding 130 inches occur in the Olympic Mountains dropping to less than 10 inches just east of the Cascades and in the eastern Snake River Valley. While this analysis includes the latest updates, it is a computerized analysis that does not take into account the complex terrain of the region, and provides a fairly crude picture of mean annual precipitation.

Because of the widely different terrain and its effect on precipitation, and as has been done in other NWS reports in the west, the region was divided into subregions, particularly for the analysis of depth-area-duration relations (Chapter 10). The region was further analyzed in the vertical to create a barrier elevation map from which adjustments to moisture can be made to account for such obstructions.

3.1 Subregional Analysis

Numerous attempts were made to subdivide the region to better represent meteorologically or climatologically homogeneous regions. Terrain distinctions were based on consideration of 1:1,000,000 scale topographic maps. Initially, these maps (World Aeronautical Chart series) were analyzed to delineate subregions where elevation in any direction changes less than 1,000 feet in 50 miles or more. This preliminary analysis resulted in two separate subregions (orographic and least-orographic) as approximately represented in Figure 3.2. Prominent least-orographic regions on this diagram are the Puget Sound and Willamette Valley along with the plateau regions in eastern Washington and Oregon, and the Snake River Valley in Idaho.

A comparison was made between Figure 3.2 and the subregional analysis in NOAA Atlas 2 (Figure 3.3). Subregions 30, 31, and 32 of NOAA Atlas 2 were identified as least-orographic and the similarities of the least-orographic regions are apparent. A more detailed subregional breakdown of the Northwest's terrain was made in the depth-area-duration analysis, as discussed in Chapter 10.

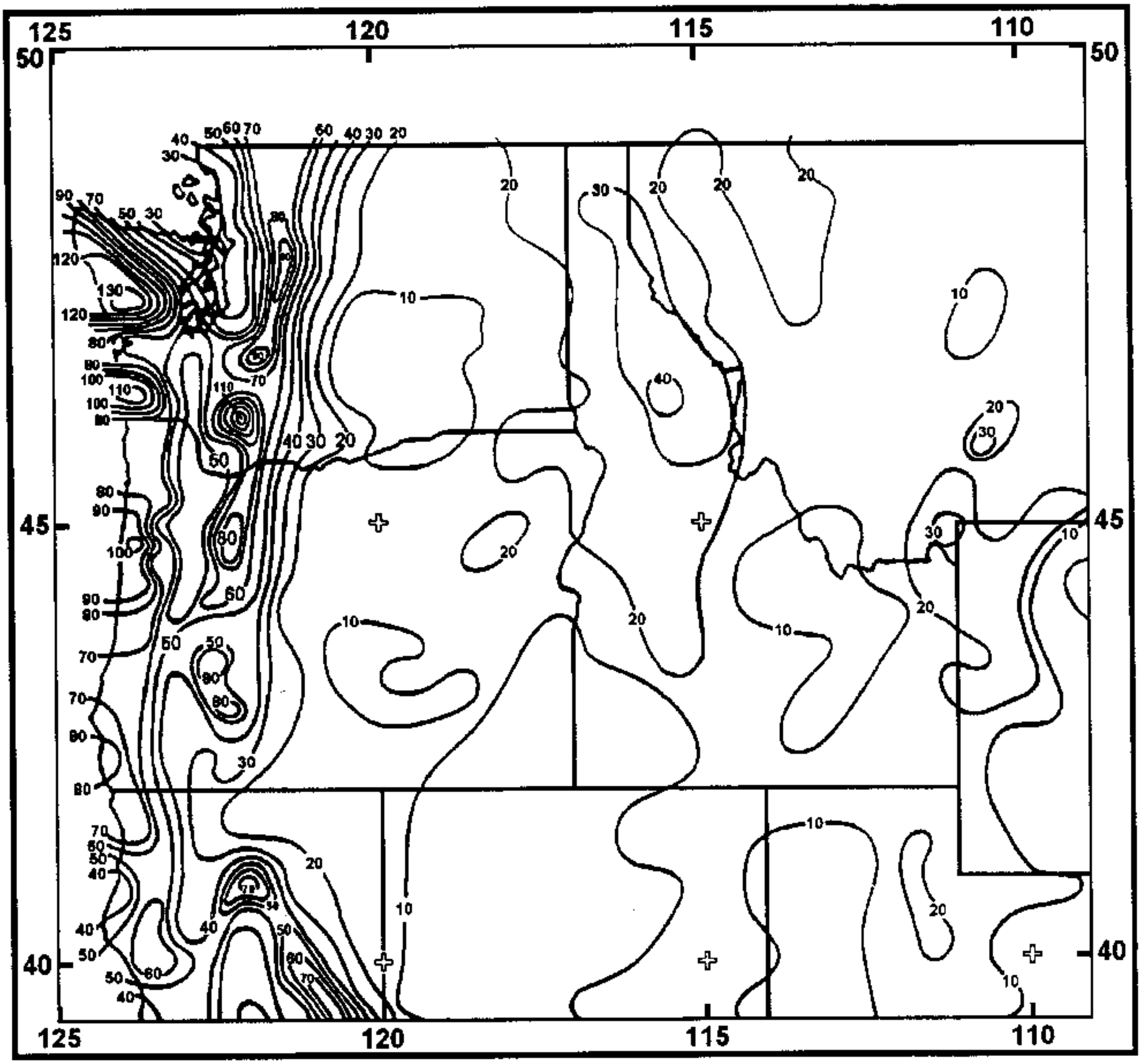

Figure 3.1.--Mean annual precipitation (inches), based on 1961-1990 normals (NCDC, 1992).

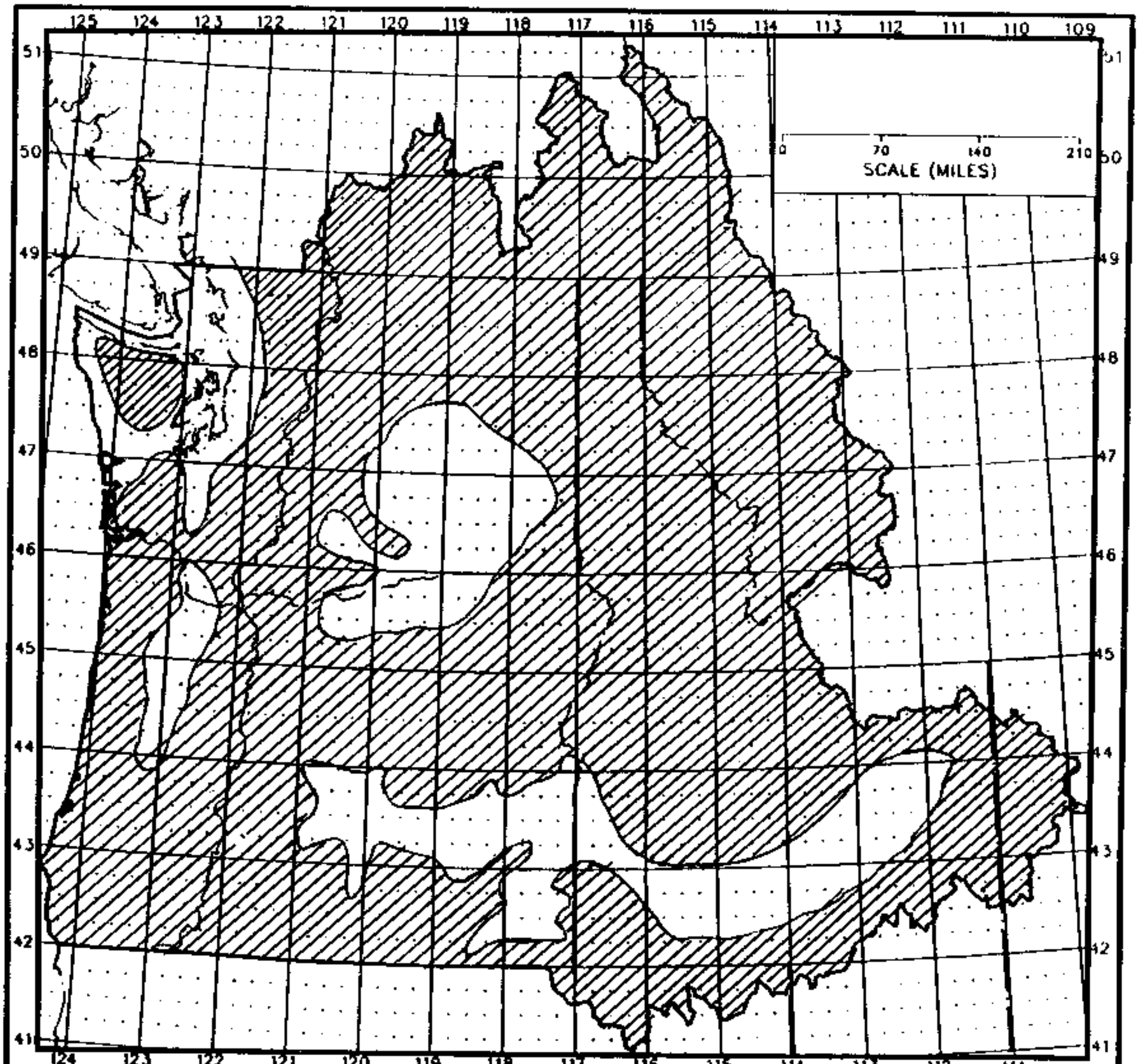

Figure 3.2.--Least orographic (non-hatched) and orographic regions (hatched).

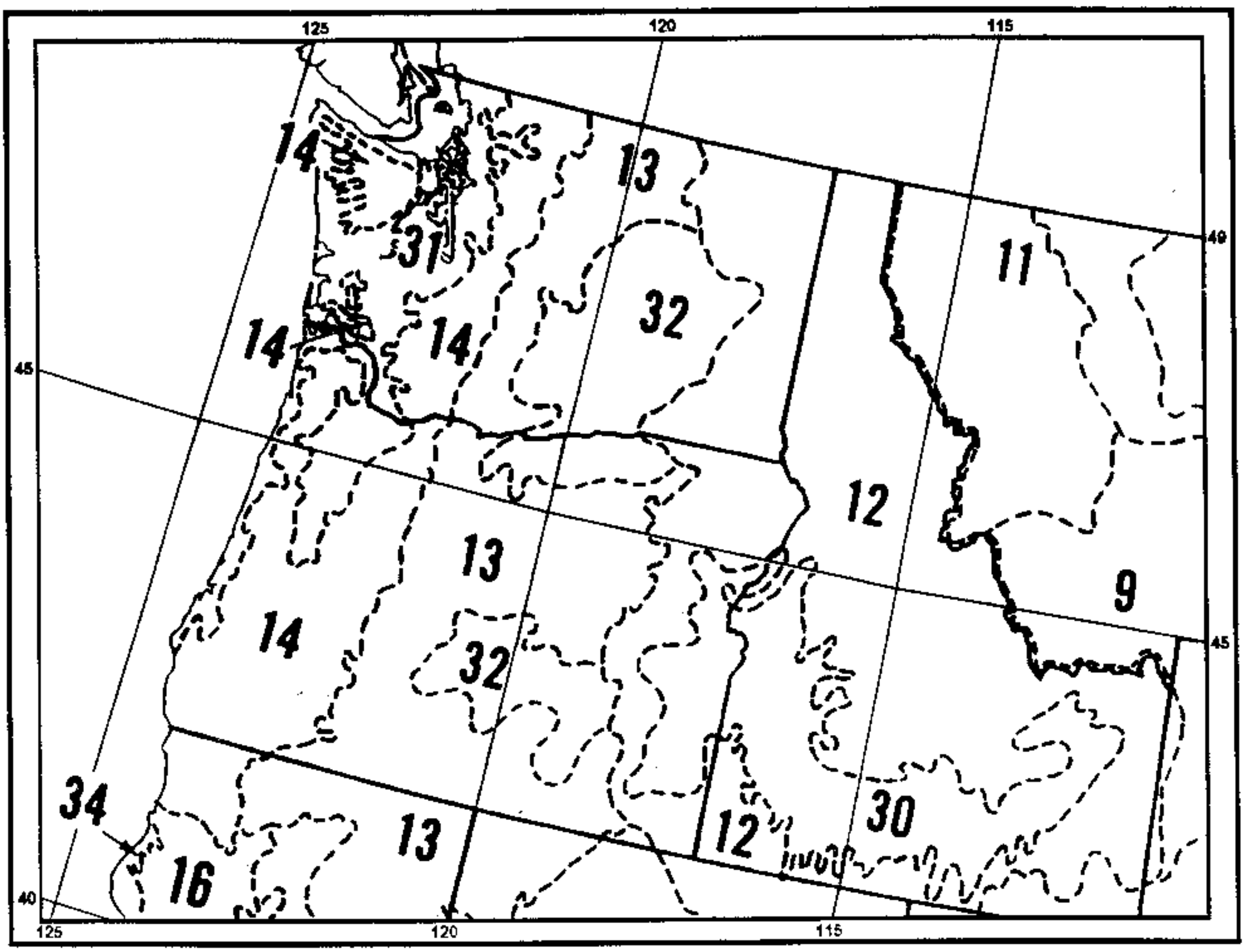

Figure 3.3.--Non-orographic regions (Nos. 30, 31, and 32) from NOAA Atlas 2.

3.2 Barrier-Elevation Map

Terrain features have a significant effect on the broadscale flow of moisture as it encounters and flows around and/or over the feature or barrier. This study followed the procedure of previous PMP studies in orographic regions by developing a barrier-elevation map. Its principal use is in making vertical adjustments to precipitation or moisture values. Barrier-elevation maps have been derived and discussed extensively in HMR 36, 43, 49 and 55A, and the technique for developing them will not be covered in as much detail here.

The analysis procedure begins with a determination of the moisture inflow directions for storms producing large precipitation amounts (Miller et al., 1973). Considering the sample of record-setting storms assembled for this report (Table 2.1), a range of optimum inflow directions was determined across the region as shown in Figure 3.4. Note that inflow winds are represented over a range of 90 degrees flowing in the direction of the arrows. As seen in Figure 3.4, most of the region receives moisture inflow from the west through the south, except in the vicinity of the Rocky and Bitterroot Mountains, where flows from the southeast through northeast dominates. At the northern end of the United States Rockies, the range of moisture inflows become more easterly to northerly. The inflows along the eastern border of the region are in agreement with those of HMR 55A. The boundary between westerly component and easterly component flows is not clearly defined, but in a broad sense runs from the United States-Canadian border near 118°W longitude southeastward to the northwest corner of Utah.

The barrier-elevation analysis in HMR 43 (Figures 3-36a and b in that report) served as a starting point for the present study. That analysis was verified using the storm inflow directions in Figure 3.4. Adjustments were made where necessary and reflected the fact that some of the directions in Figure 3.4 were not those considered in HMR 43.

North of the 49th parallel, the analysis was unique and based on extension of the approach used in the northwestern United States. No information could be found in available Canadian literature to support this analysis.

The final barrier-elevation maps were completed at 1:1,000,000 scale on which topographic features less than 10 miles in width were eliminated. A reduced scale example of this map is shown for most of the region except for southern Canada, as shown in Figure 3.5. The original hand-drawn analyses were far more detailed than the analysis in Figure 3.5, which shows only 1,000-foot intervals. This figure does show the prominent elevation maxima in the Northwest, such as the Olympic Mountains and Cascades with maximum barrier elevations exceeding 6,000 feet along the crests. Barrier elevations over 9,000 feet are found in parts of the Rockies. A rule of thumb applied to many previous studies, and applied here as well, was to close off the effects of singular barriers downwind about 1.5 times the barrier width.

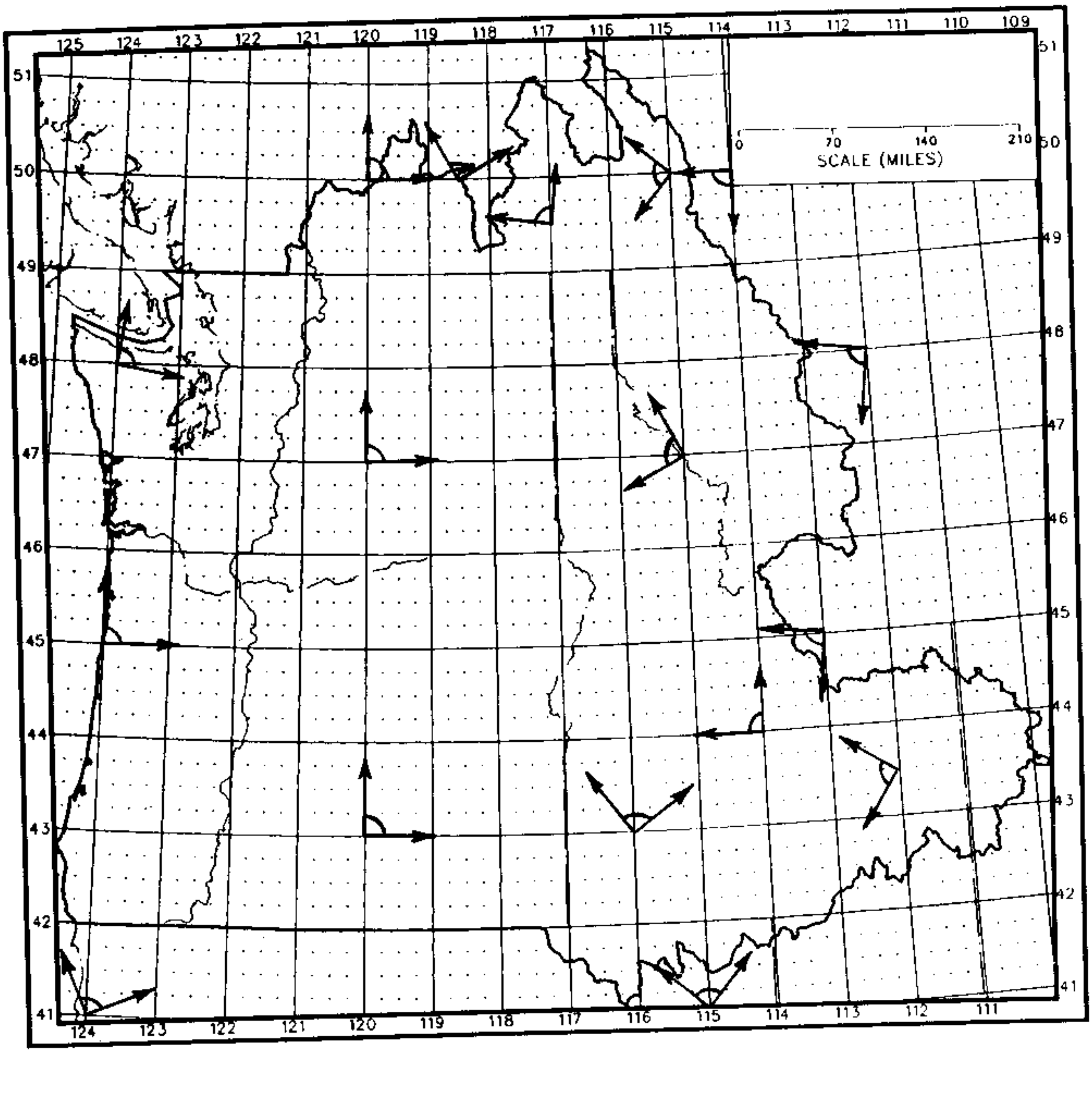

Figure 3.4.--Range of inflow wind directions producing large rains.

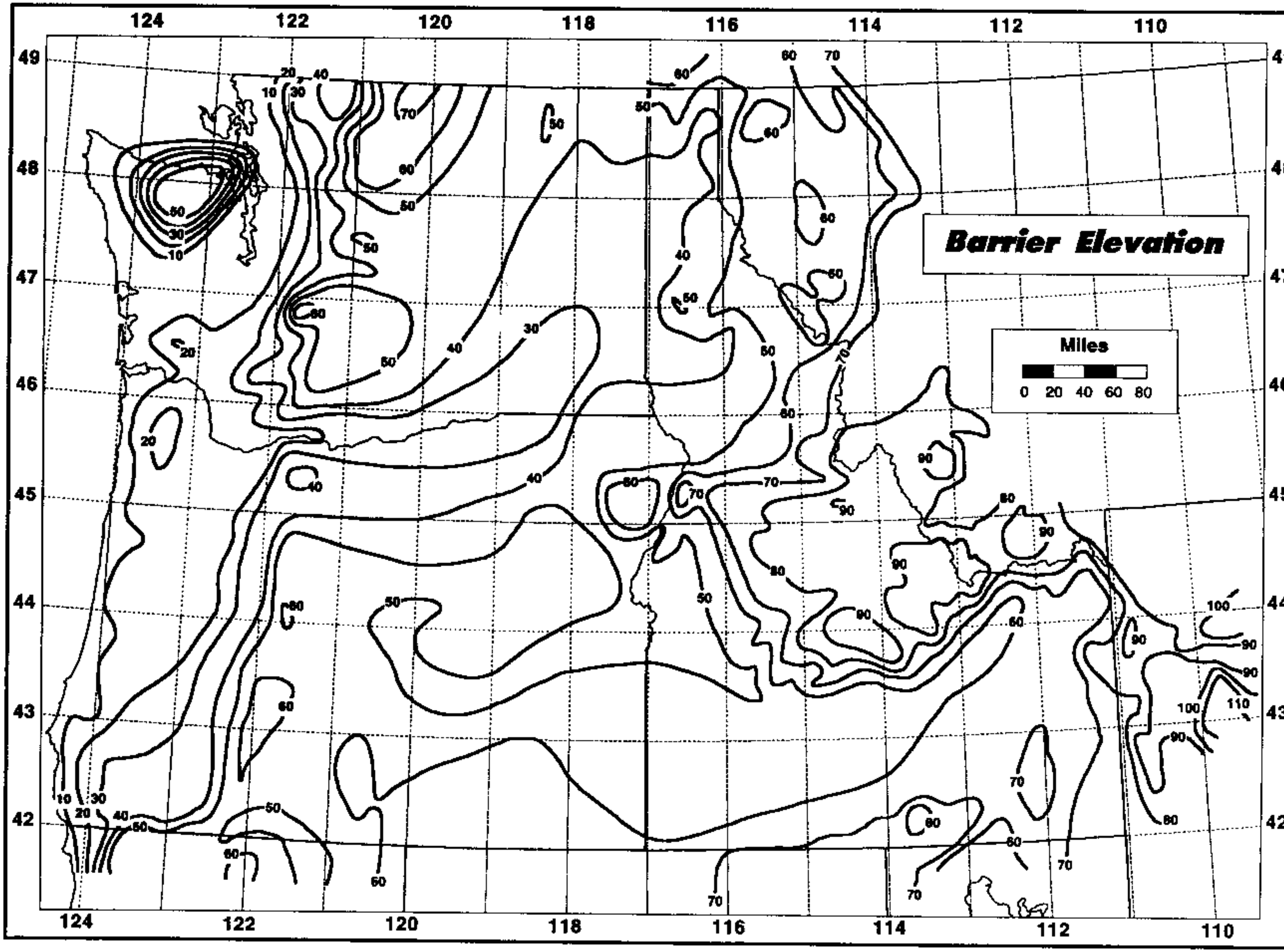

Figure 3.5.--Barrier elevation analysis in hundreds of feet, reduced from 1:1M scale.

4. MOISTURE ANALYSIS

4.1 Introduction

Atmospheric moisture is often represented by the surface dew point in PMP studies for several reasons. There are far more surface stations than upper-air sounding stations and observations are taken much more frequently (hourly vs. twice a day). Upper-air observations do allow the measurement of total vertical moisture in terms of precipitable water (USWB, 1951). However, the lower density of such stations does not allow spatial variations in low-level moisture to be accurately depicted. Additionally, a number of studies (Reitan, 1963; Bolsenga, 1965) have shown that surface dew point is an acceptable measure of water vapor aloft in the saturated atmosphere of storm periods.

HMR 43 described the seasonal variation of 12-hour maximum persisting 1000-mb dew points for the region providing both seasonal curves at selected locations as well as regional analyses for each month. In this study, these analyses were modified by using more recent data. The concept of maximum persisting dew point has been used in PMP studies for quite some time. It may be useful, however, to restate the definition. The maximum persisting dew point (for some specified time interval) is the value equalled or exceeded at all observations during the time period.

To derive the monthly 12-hour maximum persisting dew point maps, records at 36 locations were obtained from past studies (HMR Numbers 36, 43 and 49). Data on a series of computer tapes (Peck et al., 1977) through 1983 were examined for exceedances to the previous study records, after reduction to 1000 mb by use of the vertical adjustment process discussed in Section 7.3. When such exceedances occurred, they were verified against values in the Local Climatological Data (National Climatic Data Center, 1948-) and were also checked with synoptic weather information to ensure that the new records were set under conditions favorable for precipitation. When new dew point records occurred during precipitation sequences, the dew points were accepted provided that upwind trajectories from the site showed increasing dew points over time. Once the new records were determined, new annual curves were drawn at these stations. Values from these curves were plotted on monthly maps and new maps drawn. Maps of month-to-month changes of persisting dew point values were made and individual monthly maps redrawn where necessary to obtain a smooth monthly transition in persisting dew points across the study area. Monthly differences from the earlier reports were usually less than 2°F and did not exceed 3°F within the study region.

The monthly isodrosotherm analyses were extended into British Columbia based on information in Verschuren and Wojtiw (1980), supplemented by additional station data supplied by the Canadian Atmospheric Environment Service. These data were handled in the same manner as were the United States data.

4.2 Revised Monthly Maps of 12-Hour Maximum Persisting Dew Point

A revised set of monthly 12-hour maximum persisting 1000-mb dew point maps was prepared for this study from the data described above. The maps are shown in Figures 4.1 to 4.12. Some smoothing of the results was necessary in order to assure that a smooth transition existed between each month at all locations. To do this, numerous seasonal curves were plotted, as shown by three examples in Figure 4.13.

The 12-hour maximum persisting dew points in Figures 4.1-4.12 are an update to HMR 43 and are used in a number of applications in this study to adjust station moisture for elevation. Hogg (personal communication, 1993) has pointed out that direct analysis of precipitable water using upper-air data could also be done, since more upper-air data are now available. While it was not possible to investigate the effects of Hogg's remarks within the timelines of this study, a recommendation for further study in this area may be appropriate.

A study by Tomlinson (EPRI, 1993b) has recommended that, on the basis of studies conducted for the Great Lakes region, average maximum dew points are better indicators of inflow moisture than are 12-hour maximum persisting dew points. It was also suggested that the duration of averaging be more consistent with the length of critical precipitation. Both of these suggestions warrant additional consideration and in particular, their application to other regions needs to be addressed. However, these ideas were too late to be considered for the present study.

In Figure 4.14, the Northwest region is partitioned into cool season (October-March), warm season (April-September) and any-season (January-December) subregions. These subregions correspond to the months in which the largest daily precipitation amounts have been observed most frequently. Isodrosotherms were drawn for each of the three sections by averaging the indicated monthly dew point values at all locations within each section. The analyses were then combined by smoothing across sectional boundaries. The result was the "multi-seasonal" 12-hour maximum persisting dew point map shown in Figure 4.15. This map was used to adjust all transposed 1000-mb free atmospheric forced precipitation (FAFP) values in the region to their respective barrier elevations. It was used for the same purpose with 100-year, non-orographic precipitation values to create the orographic parameter, T/C (Chapter 7).

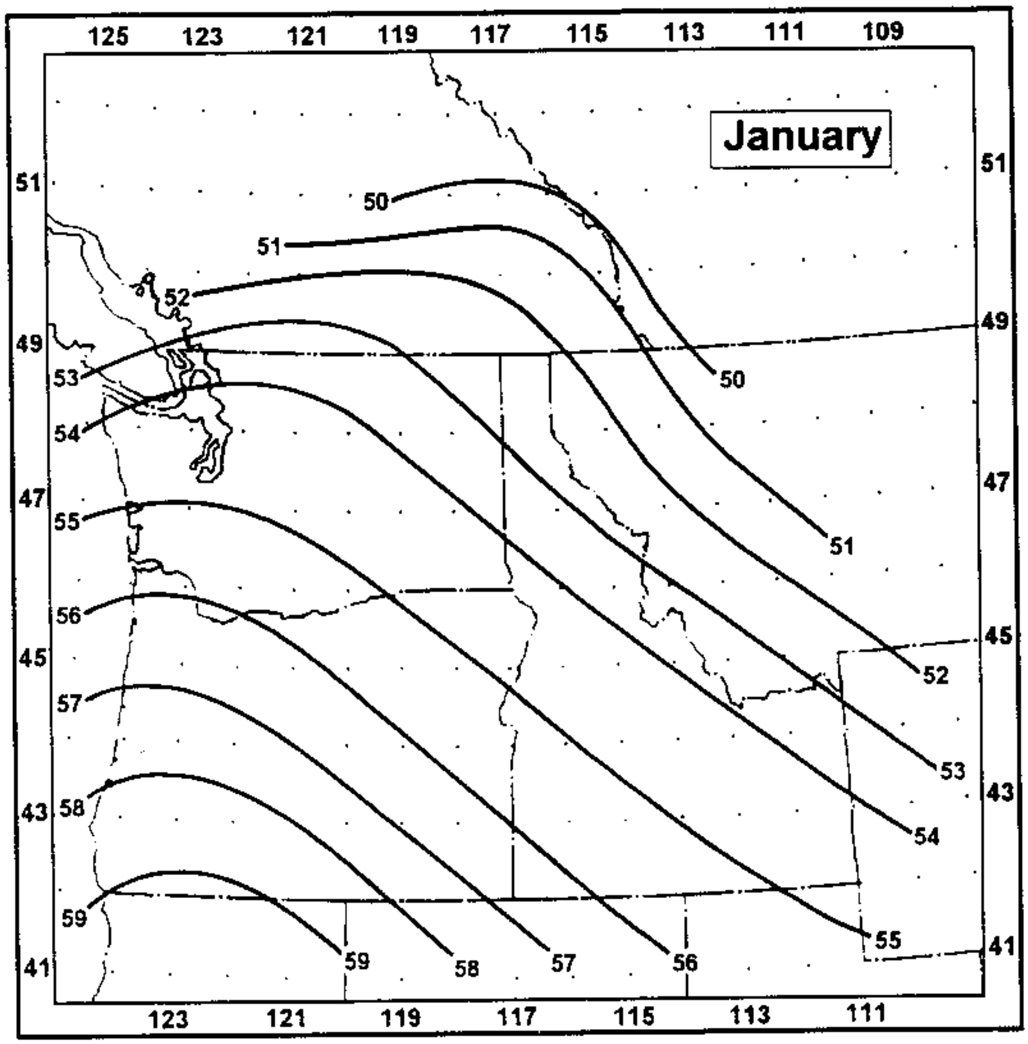

Figure 4.1.--12-hour maximum persisting 1000-mb dew point analysis (°F), January.

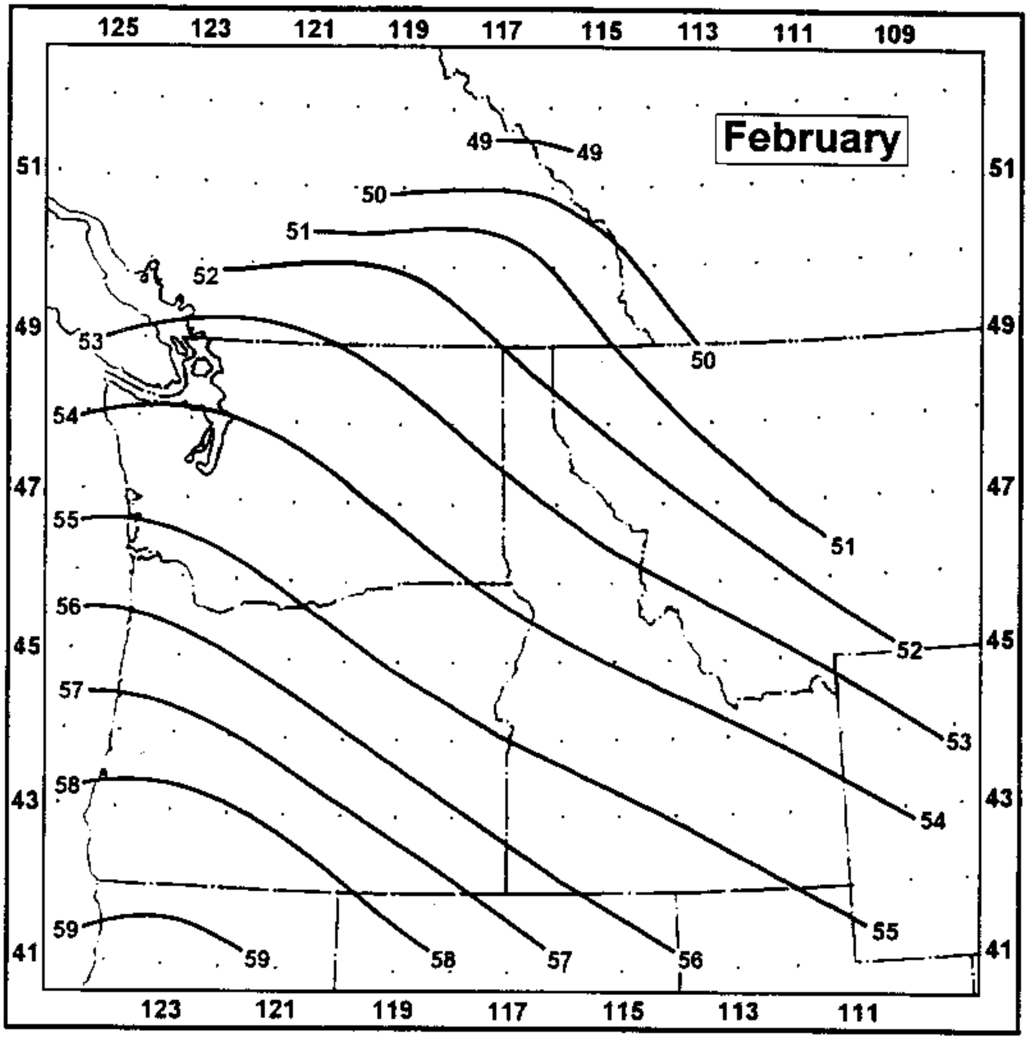

Figure 4.2.--(see Figure 4.1), February

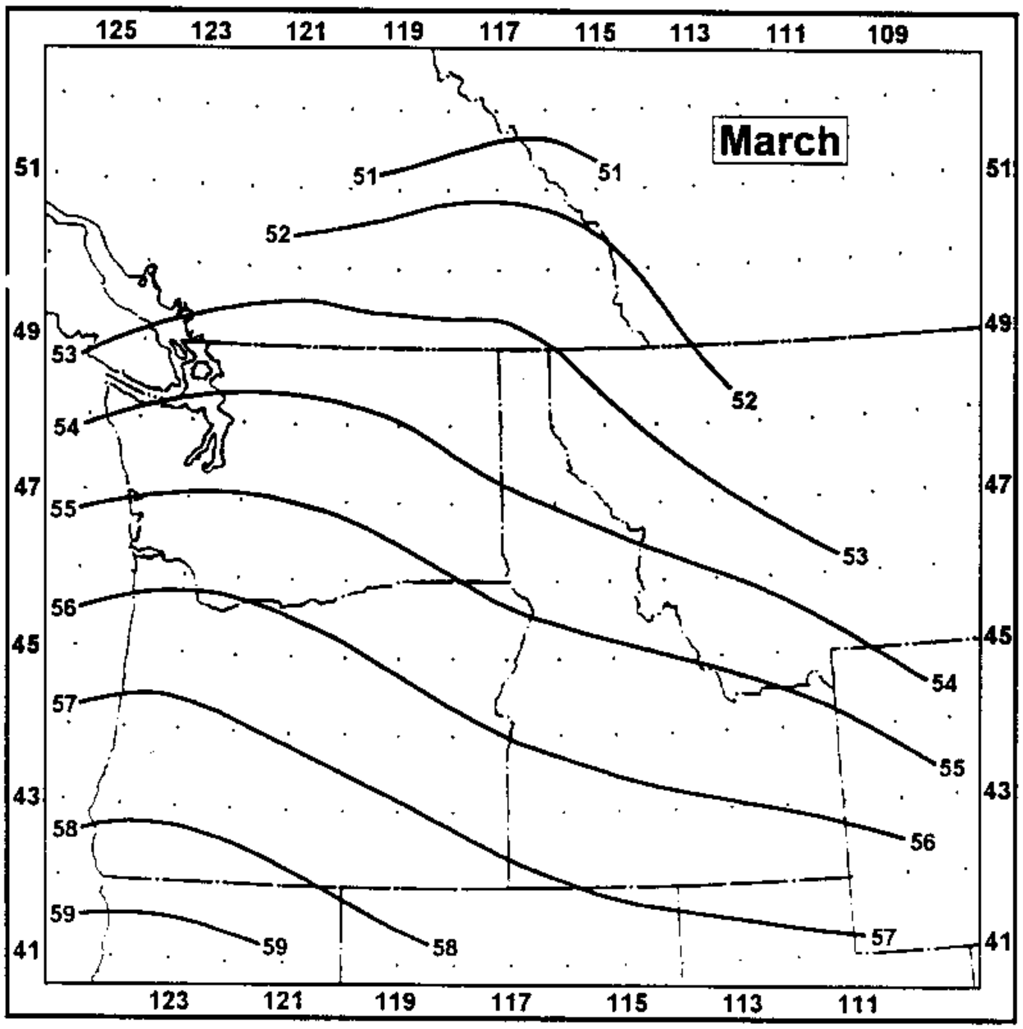

Figure 4.3.--(see Figure 4.1), March.

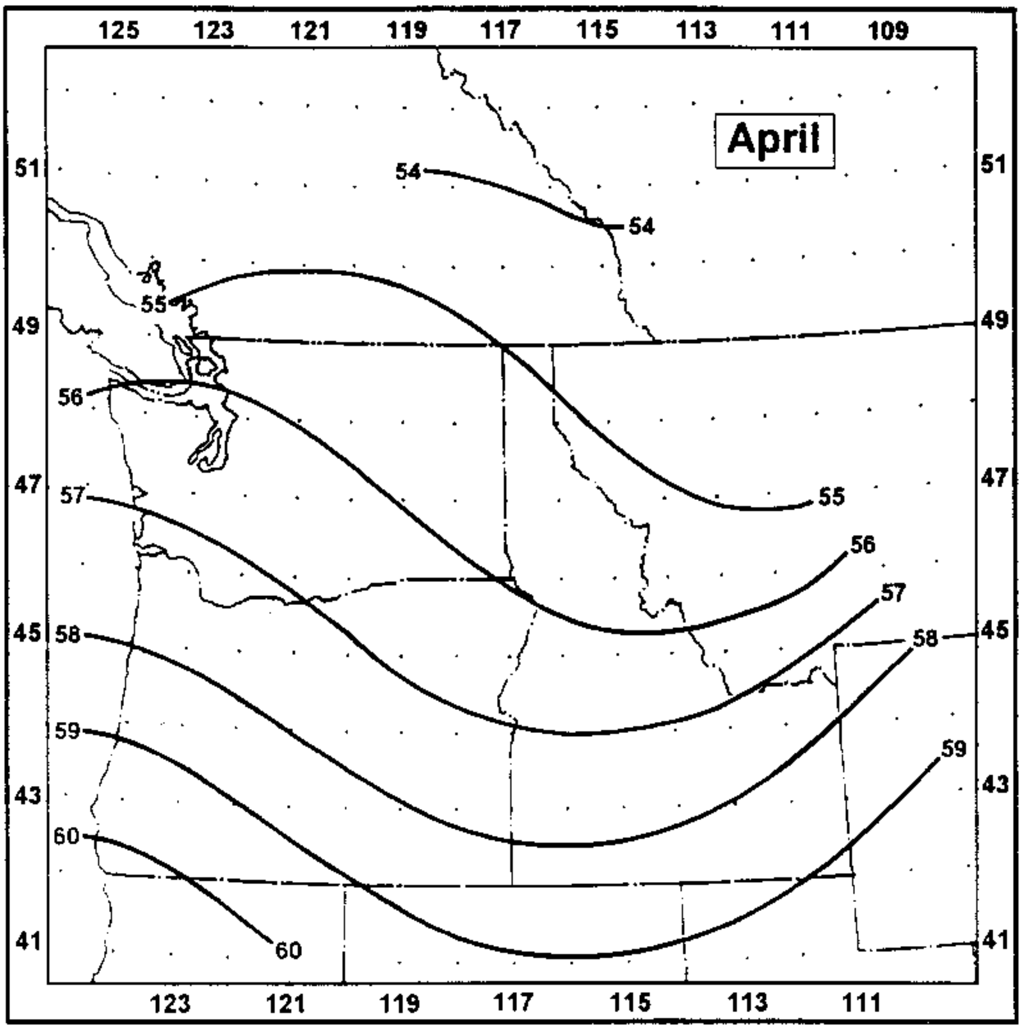

Figure 4.4.--(see Figure 4.1), April.

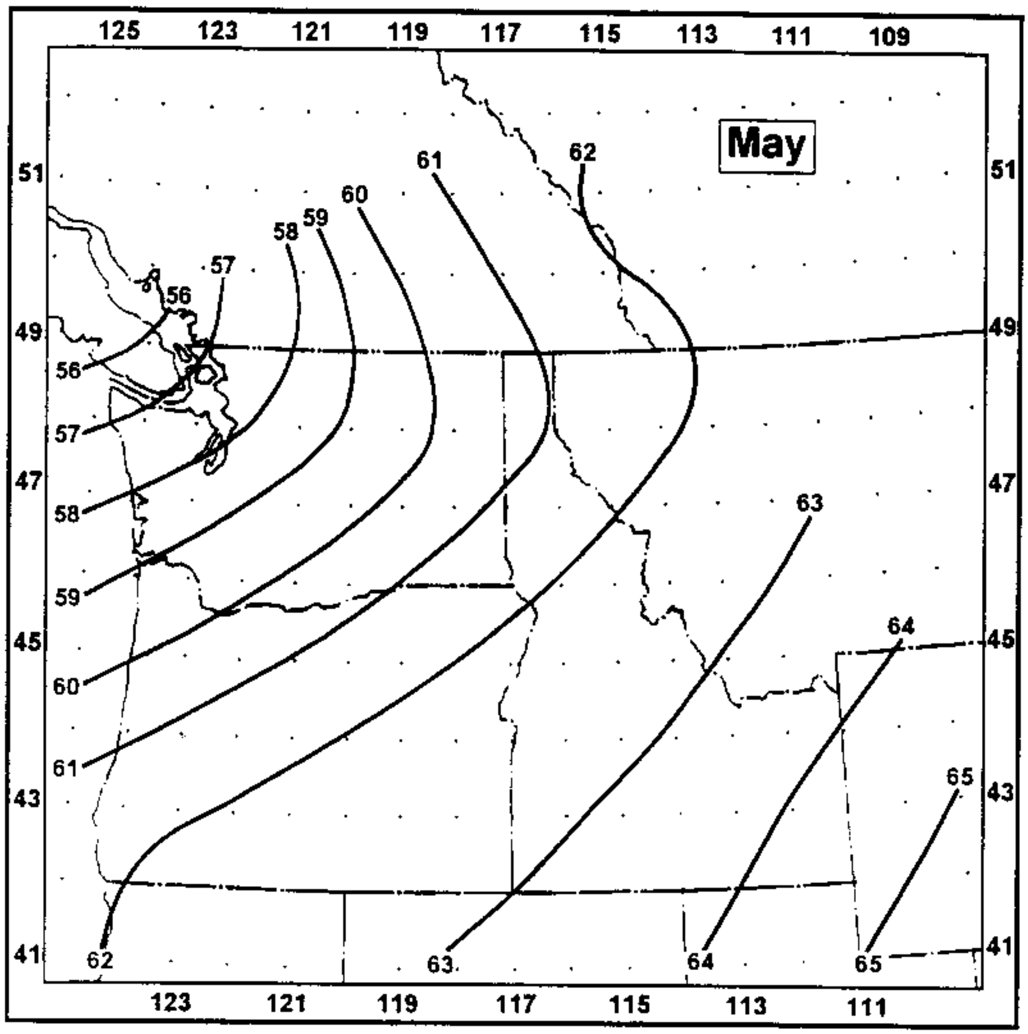

Figure 4.5.--(see Figure 4.1), May.

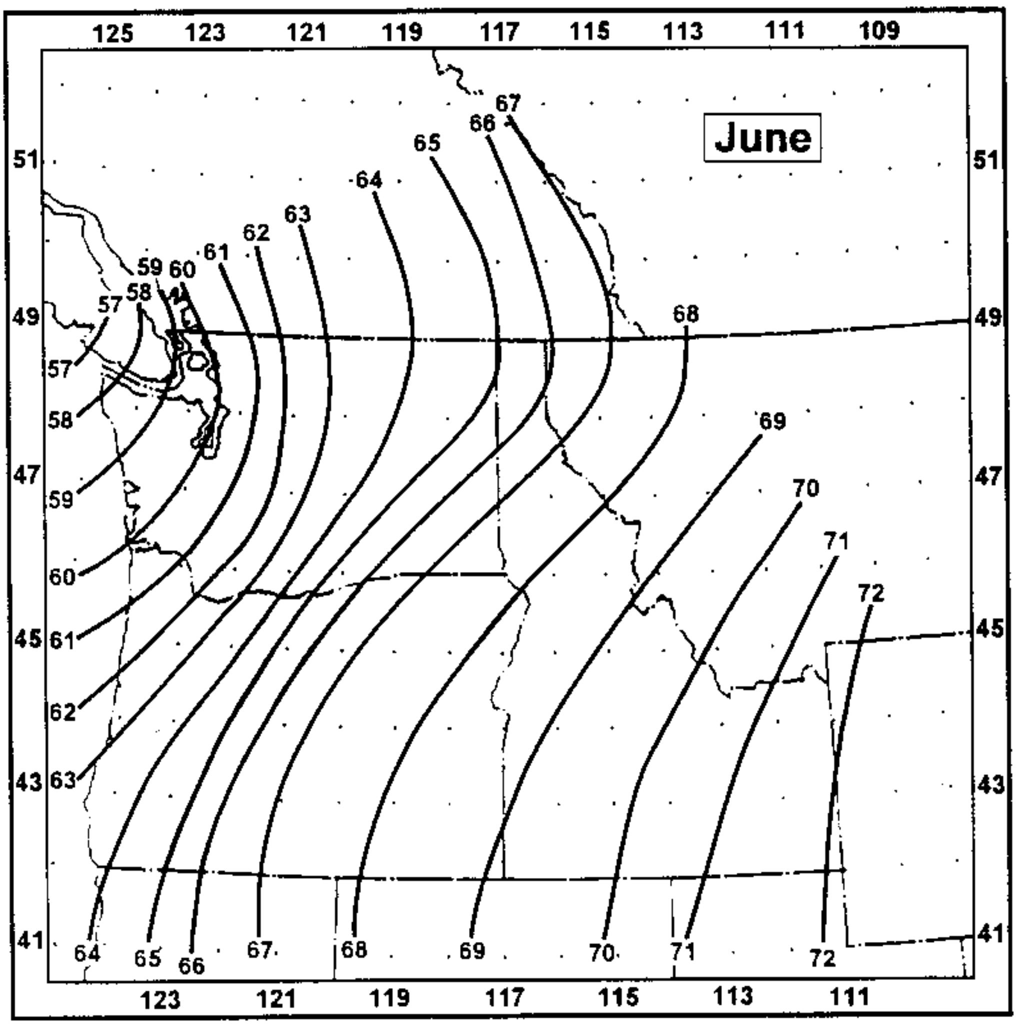

Figure 4.6.--(see Figure 4.1), June.

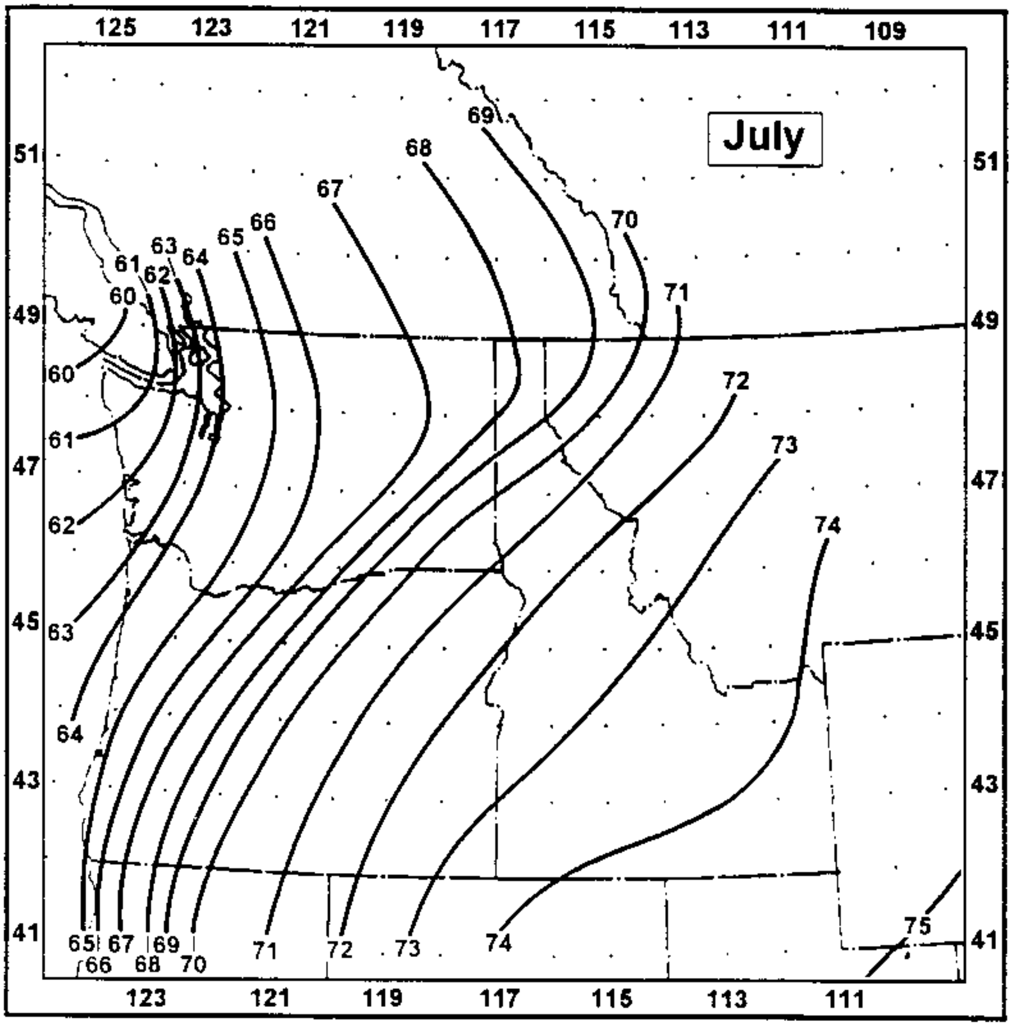

Figure 4.7.--(see Figure 4.1), July.

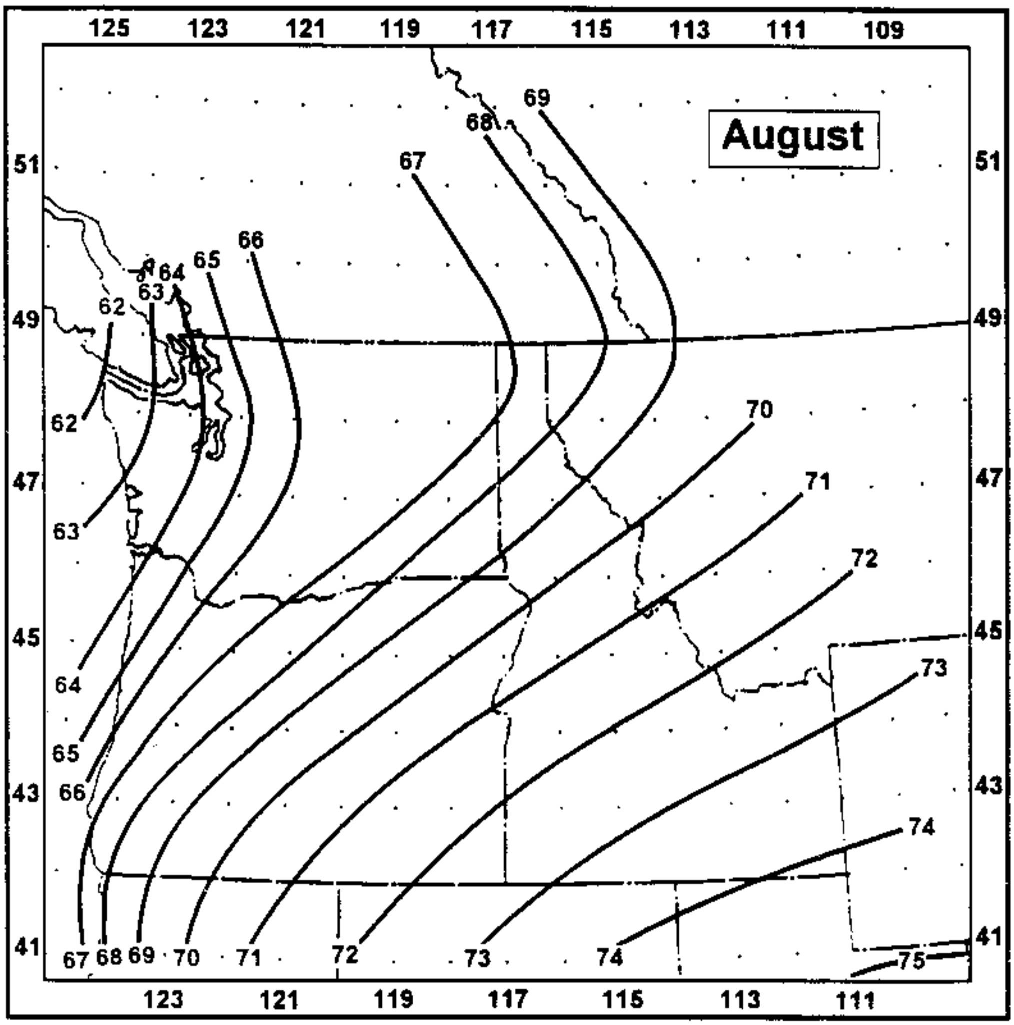

Figure 4.8.--(see Figure 4.1), August.

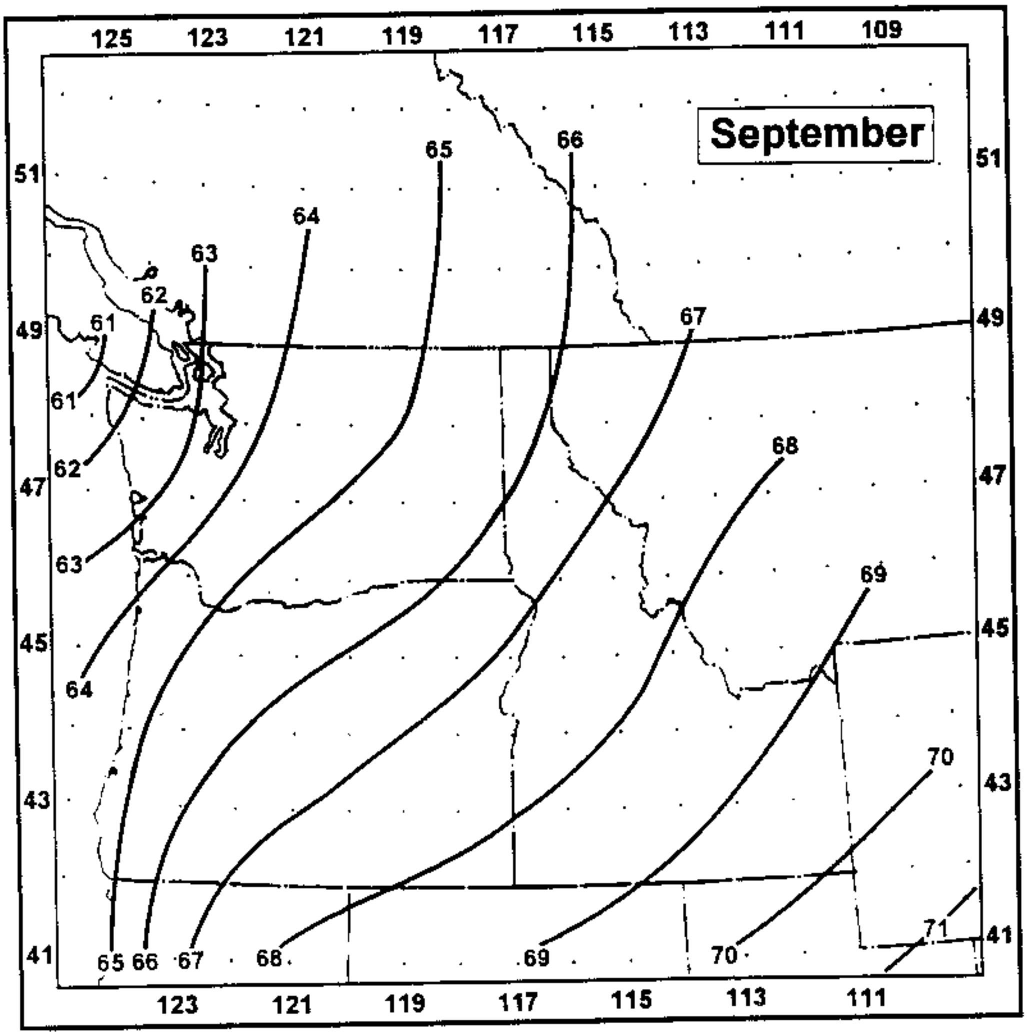

Figure 4.9.--(see Figure 4.1), September.

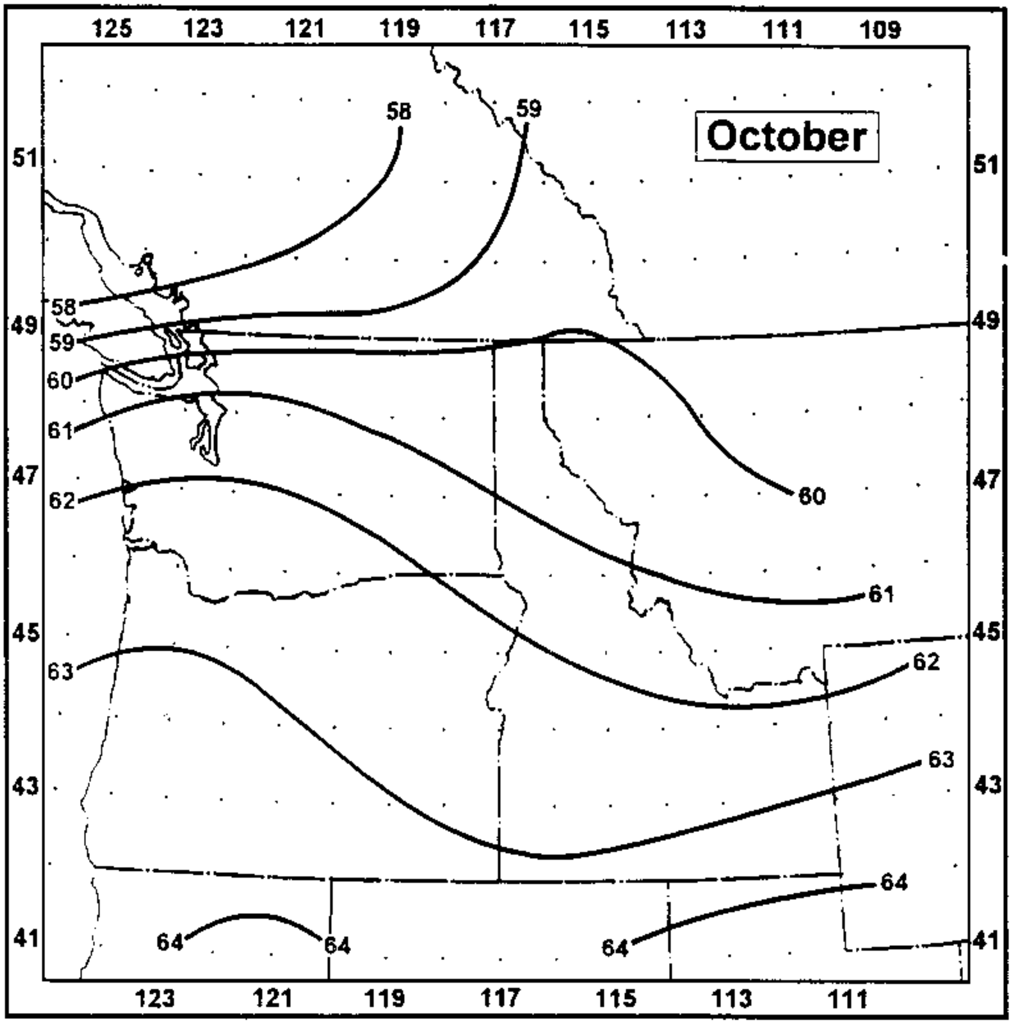

Figure 4.10.--(see Figure 4.1), October.

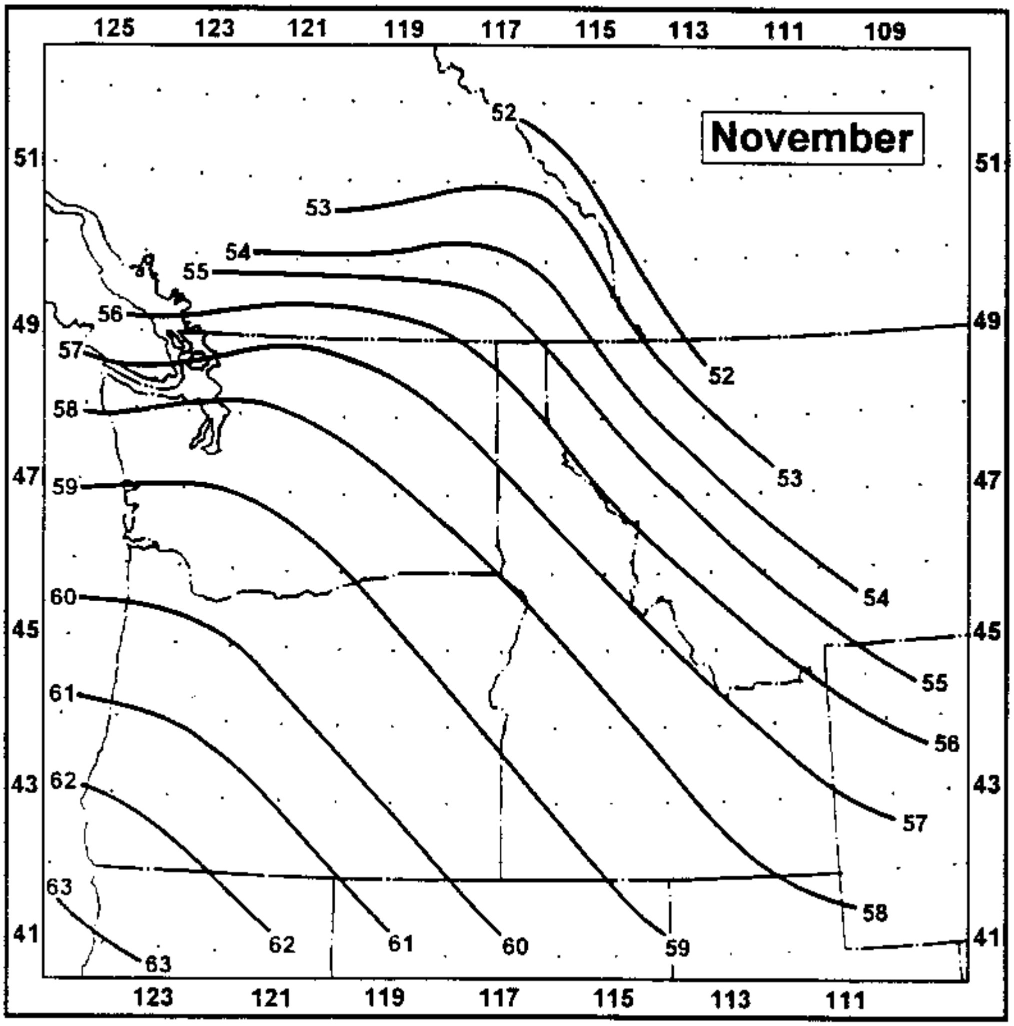

Figure 4.11.--(see Figure 4.1), November.

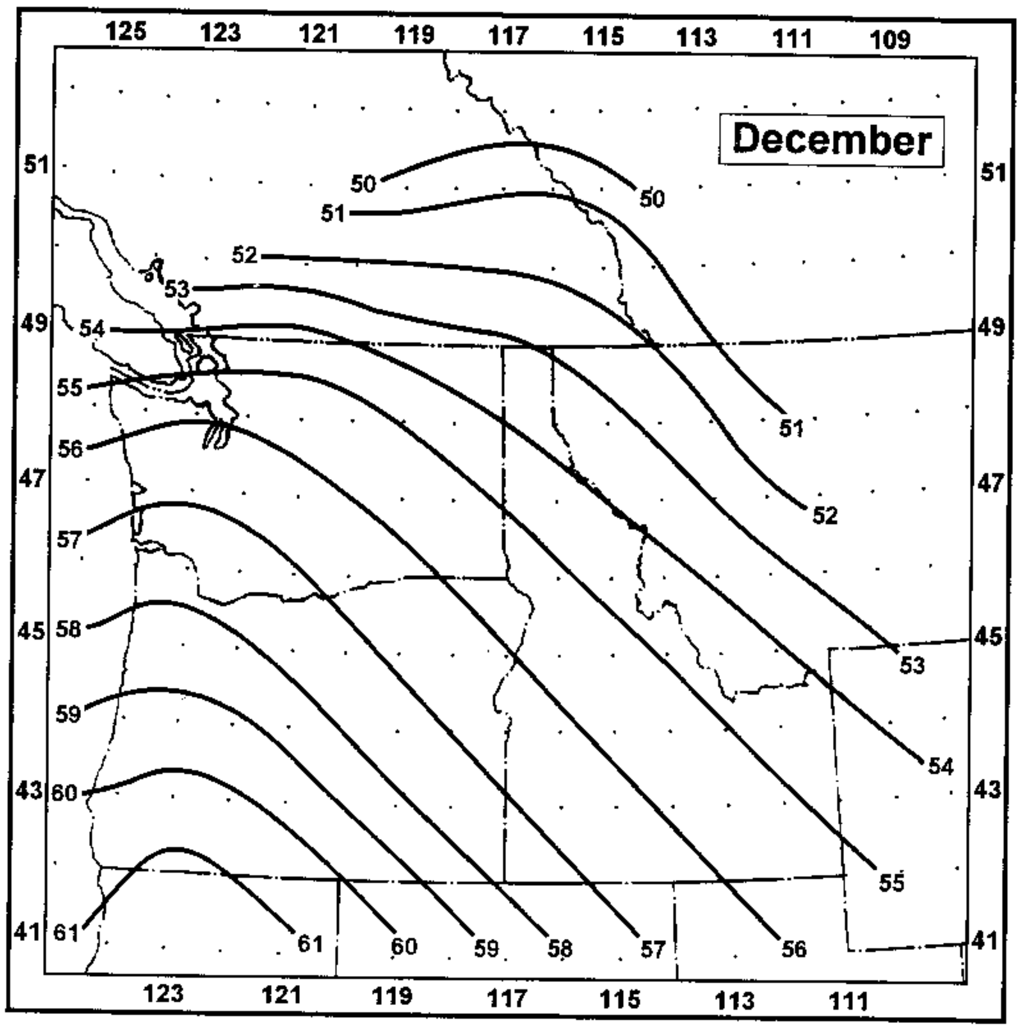

Figure 4.12.--(see Figure 4.1.), December.

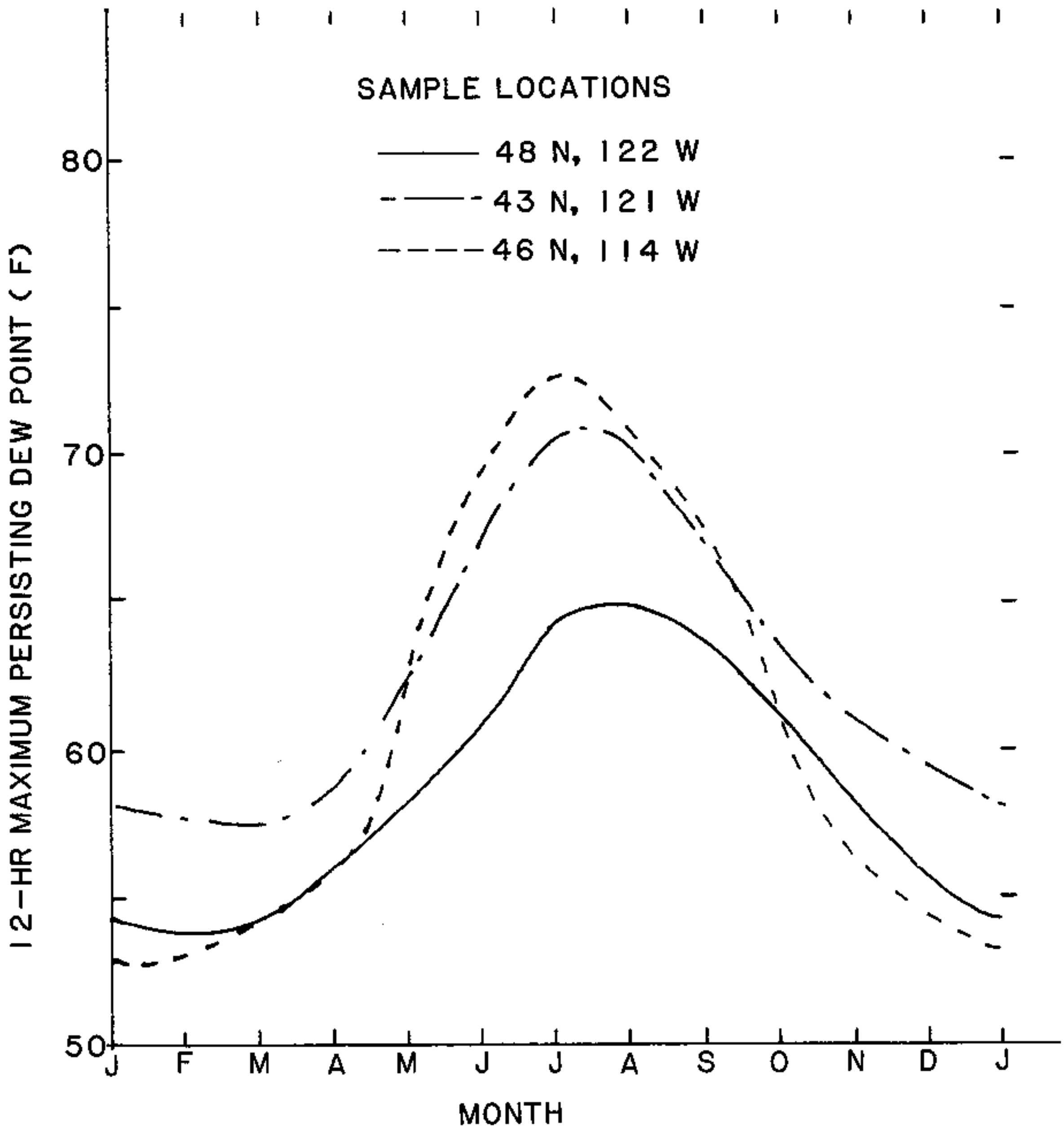

Figure 4.13.--Samples of smooth seasonal curves for selected locations (from Figs. 4.1-4.12), 1000-mb, 12-hour maximum persisting dew point (°F).

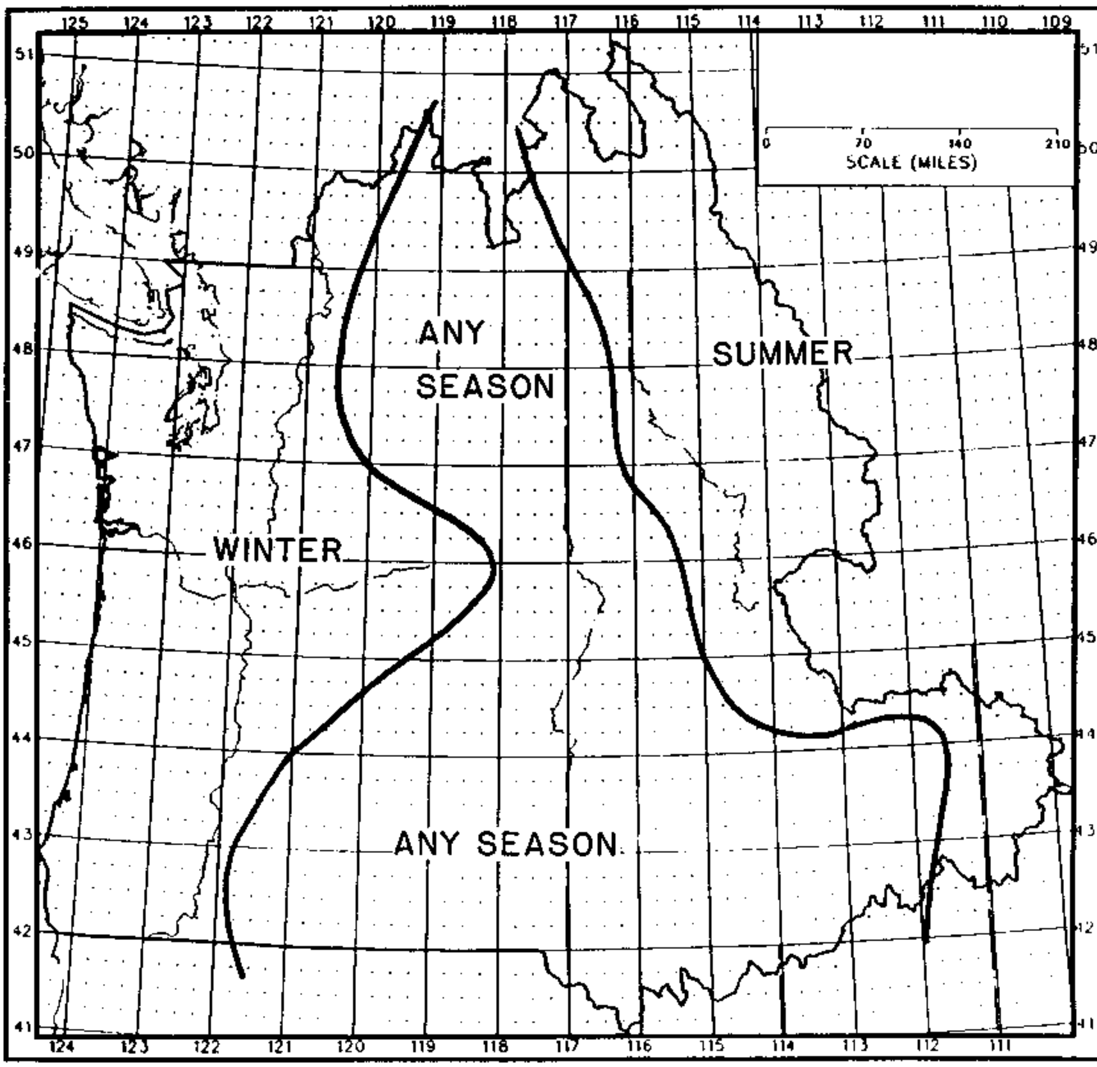

Figure 4.14.--Seasonal subregions for maximum daily rainfalls.

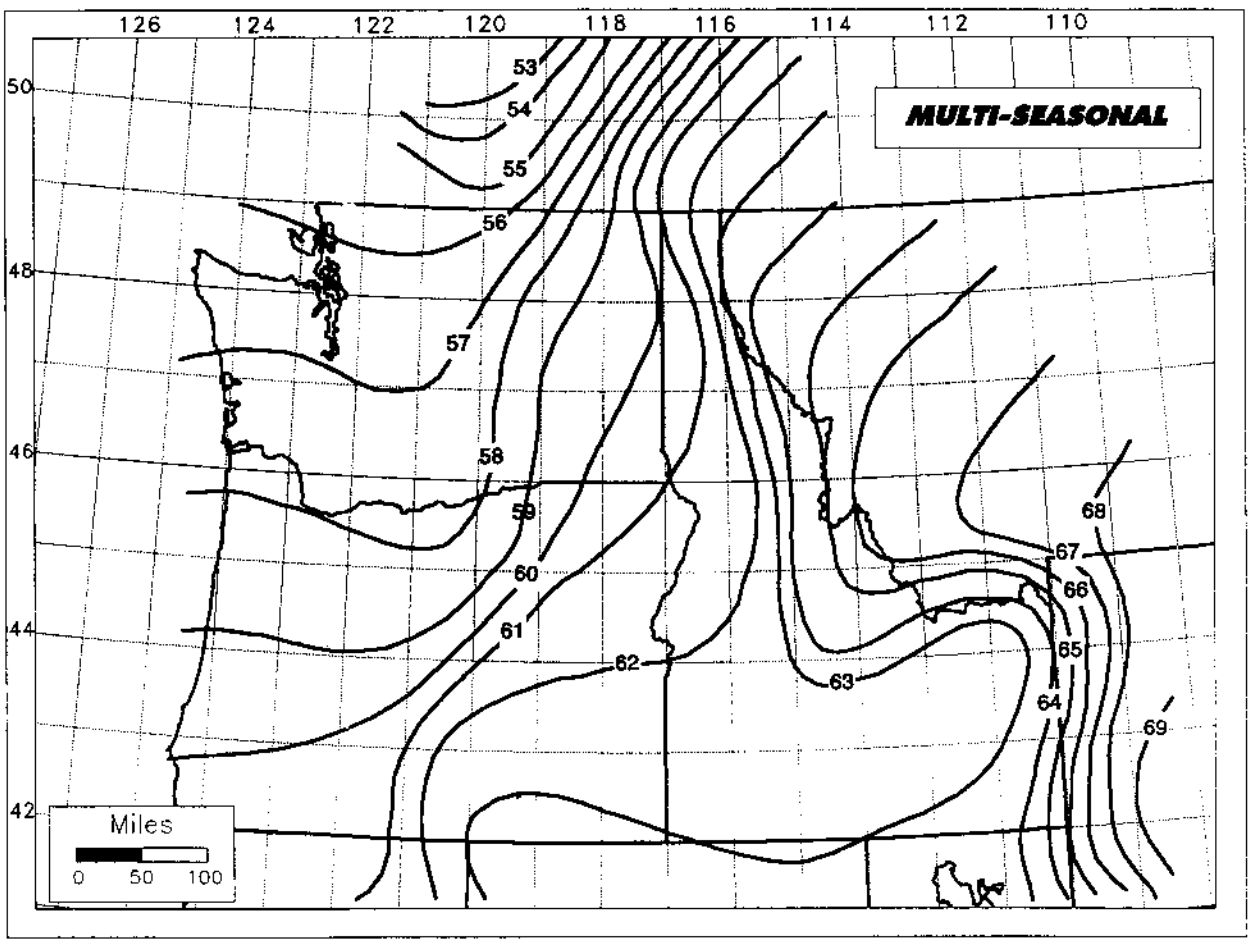

Figure 4.15.--Multi-seasonal maximum persisting dew-point analysis (1000 mb, °F).

4.3 Determination of Storm Dew Points

Just as it is important to determine the 12-hour maximum persisting 1000-mb dew points, it is equally important to obtain dew points representative of the moisture contributing to individual storms considered as major events. The ratio of maximum to storm persisting dew points (both converted into precipitable water) is taken to define the potential for precipitation increase in the storm maximization process.

In the traditional method for storm maximization, primarily in the non-orographic regions, it is customary to seek surface dew points along the inflow trajectory from a moisture source to the storm site. This effort is sometimes referred to as "finding the reference location" for a particular storm. Reference locations have been annotated in NWS files for almost all storms listed in the Storm Catalog (USCOE, 1945-). However, in mountainous or coastal regions, the likelihood of finding adequate storm reference dew points is small. Furthermore, where some reference locations have been analyzed as far as 1000 miles from the storm site (HMR Numbers 51 and 55A) for storms in the eastern United States, it is very difficult to locate adequate inflow dew points for storms located close to coastal regions, as is the case for most storms in this study.

In the past, for storms occurring along coastal zones, reference has been made to dew points taken at sea if available, but also to sea surface temperatures (SST), since it is assumed that in most high moisture situations the SST represents the maximum limit that could be reached by a dew point over the ocean.

Therefore, in this study, extensive consideration was given to SST analyses. The warm air flowing into many of the storms in the study region (those whose centers are west of about 121°W) crosses a region of persisting and relatively cold SST along the coastline and westward to around 130°W. During these crossings, the dew point representative of the warm air mass could be altered. In such situations the boundary layer air, chilled by these cold coastal currents, acts as a desiccator or sink for part of the low-level moisture flowing toward the eventual storm site. This moisture is "left behind" in the form of fog, cloud or drizzle as the inflowing air rides over the more dense boundary layer zone. Parcels of inflowing air, besides being desiccated, may also become mixed through turbulent interactions or by diffusion with parcels of lower moisture content air from the boundary layer air while in transit to the storm site. The net result of such passages is that the "representative" moisture content of the original air is reduced by some percent within its lower layer. What is not certain is how to calculate what the size of this hypothetical reduction would be, since input data from the historical storms is extremely limited or altogether lacking.

It appears, however, that the uncertainty in the precise amount of moisture reduction on a specific historical occasion is not critical in determining an in-place maximization factor, since this factor will change little from its value based on the